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Trillion

Oriented Crystals Breaking Down the Challenges in Accelerator Physics, Particle Physics, and Space Science — and their Simulation with Geant4

Marie Curie Global Fellowships, Project TRILLION GA n. 101032975

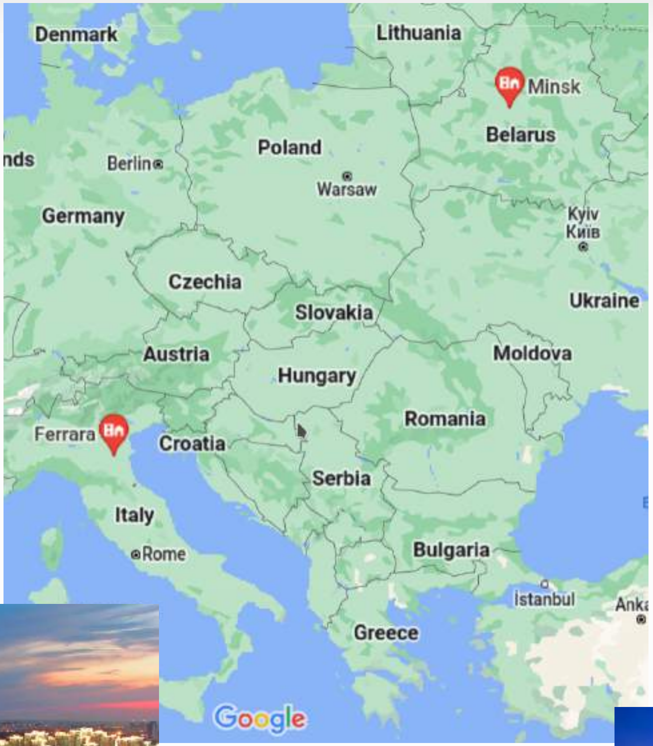
Dr. Alexei Sytov

DESY, Hamburg, 14/05/2024

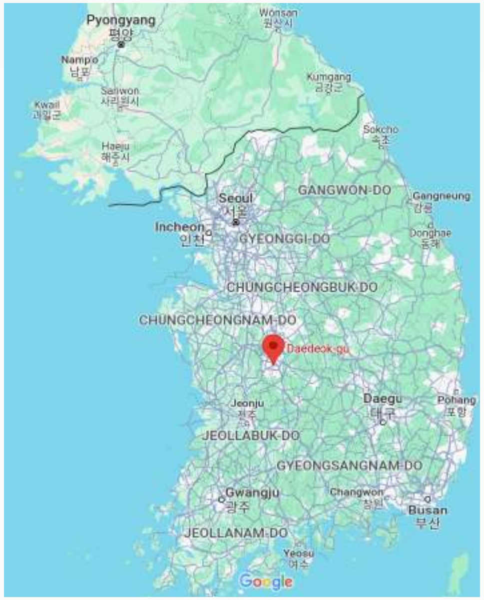
Where I am from?

I work in
Italy, Ferrara

Originally I am from
Belarus, Minsk

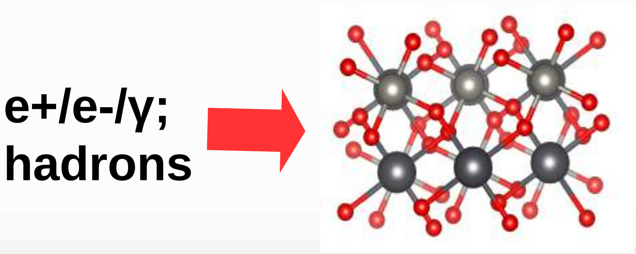


I spent almost 2 years in
Daejeon, Korea



Briefly about me

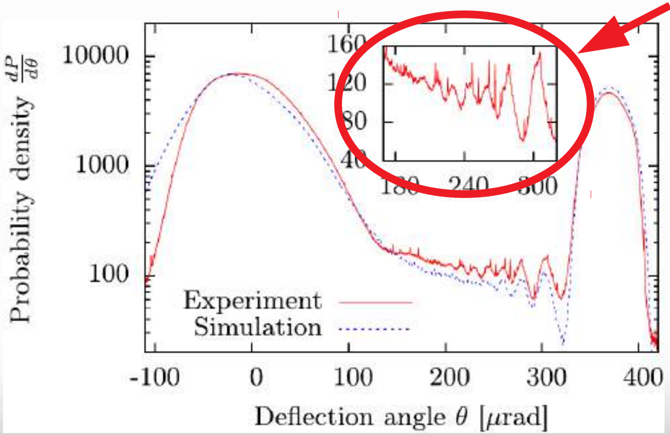
- **2018: 2 PhDs –** in Experimental Physics, University of Ferrara and in Theoretical Physics, Belarusian State University
- **2019-2021**: **Post-doctoral Fellow** in Experimental Physics at the INFN Division of Ferrara.
- Since **2020** involved in **MC_INFN** – INFN **Geant4** project
- Since **02/09/2021**: Marie Sklodowska-Curie Action Global Individual Fellowships, GA n. 101032975 – project Trillion
- **My field**: **Electromagnetic effects** of charged particles interaction with **oriented crystals** (deflection, radiation and pair production) and their applications in **accelerator physics**, **detector physics**, **nuclear physics**, **medical physics**.
- **Effects**: **Channeling**, channeling radiation, coherent pair production



Briefly about me

- **New effect predicted and observed experimentally**: **Quasichanneling oscillations** in the deflection angle distribution*
- **Software designed**: **CRYSTALRAD** simulation code – simulations of channeling, channeling radiation and crystal-based extraction from an accelerator.
- **High Performance Computing experience**: HPC Monte Carlo simulations, usage of **CINECA** supercomputing center resources since 2015, **PI** of 5 projects.
- **Additionally**: Fortran, C/C++, Mathematica, Python, Geant4, Keras deep learning framework.
- Since 2022 member of

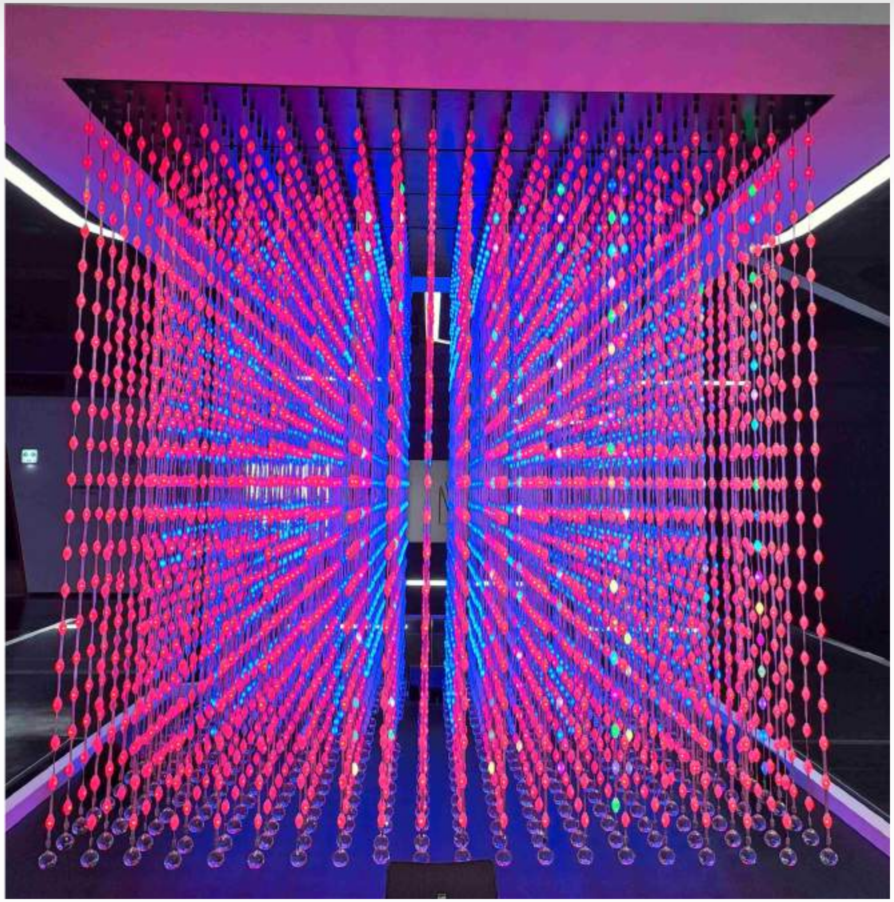
GEANT4
A SIMULATION TOOLKIT



Quasichanneling oscillations

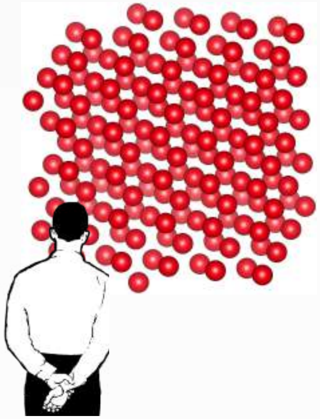
*T. N. Wistisen, …, and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

How an oriented crystal looks like

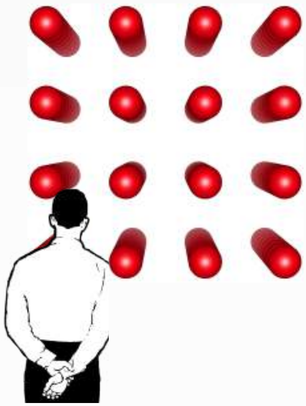


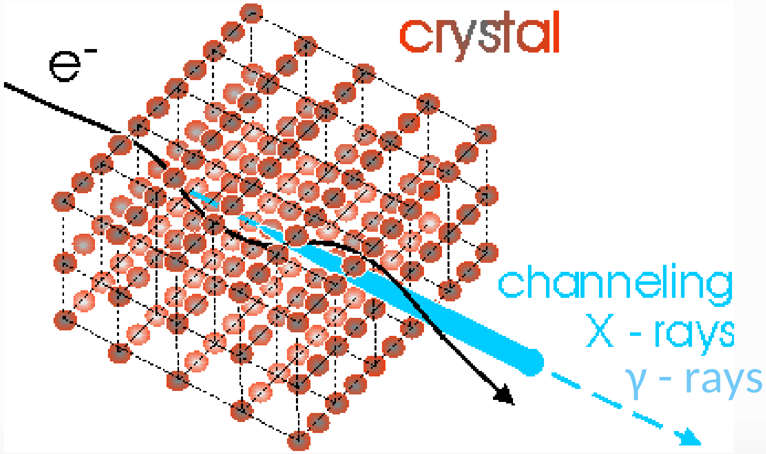
from National Science Museum, Daejeon, Korea

Non-oriented crystal

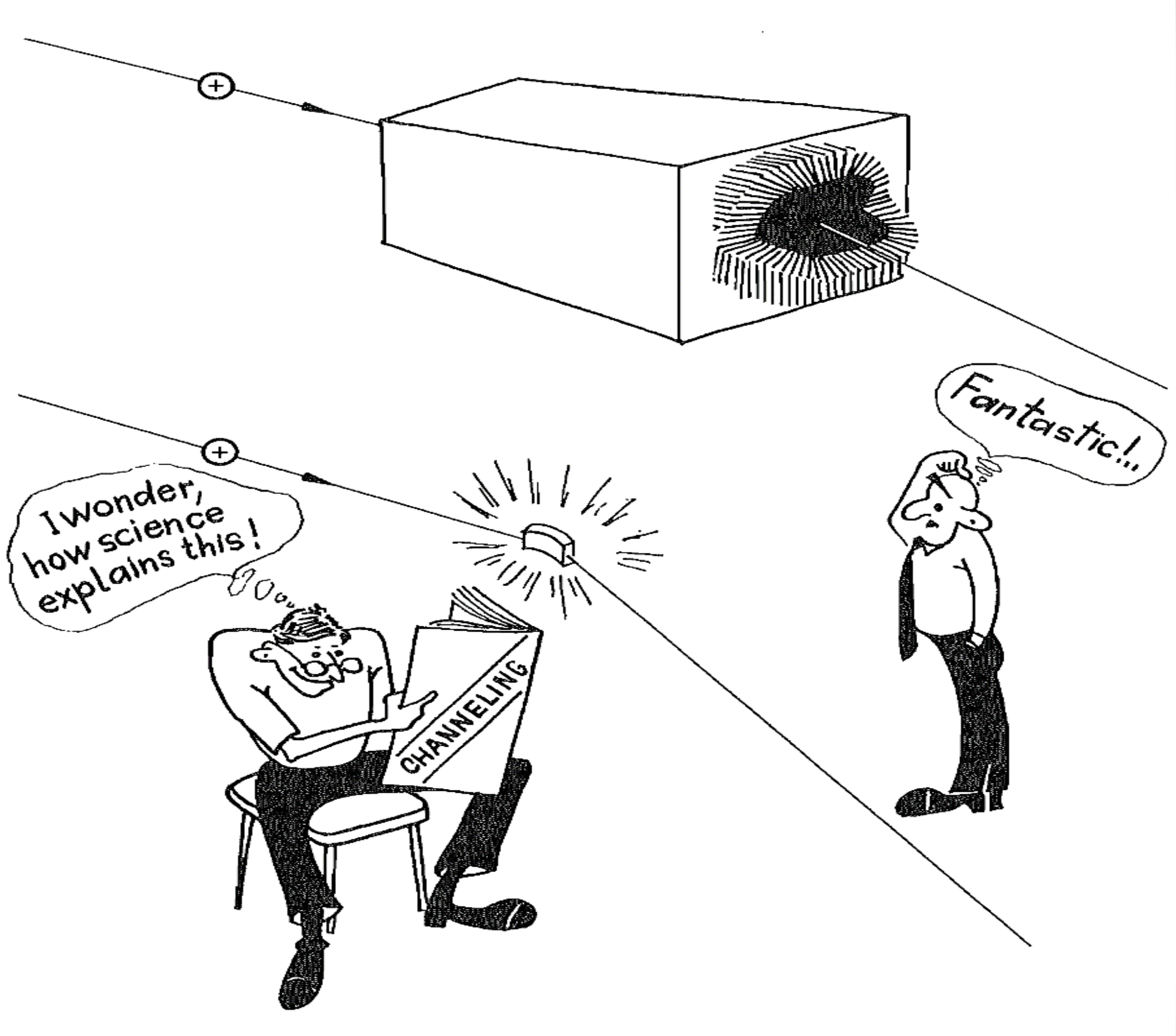


Oriented crystal

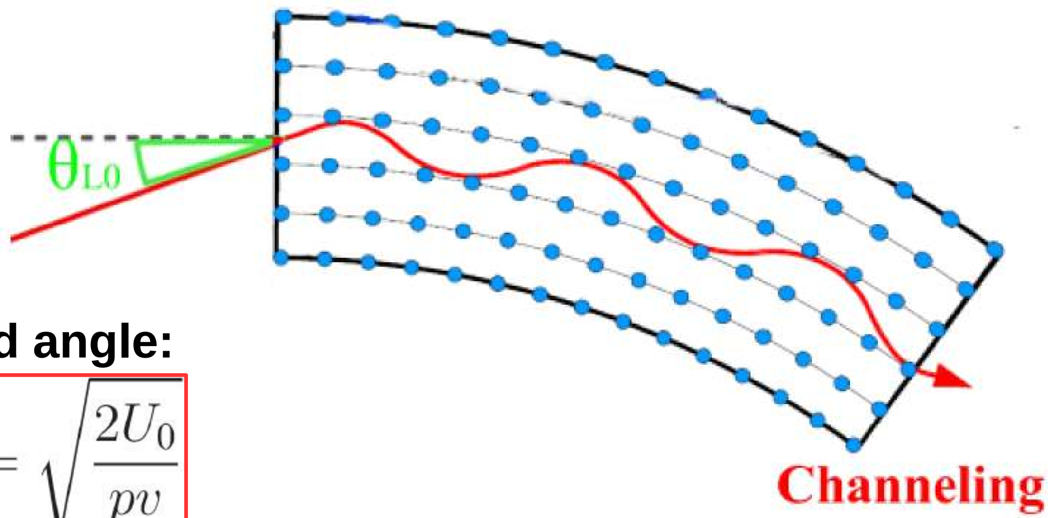


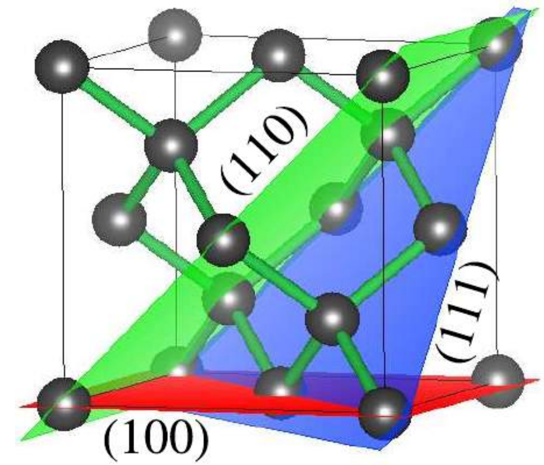


The world of the channeling effect



Channeling effect*





Lindhard angle:

$$\theta < \theta_L = \sqrt{\frac{2U_0}{pv}}$$

Channeling* **is the effect of the penetration of charged particles through a monocrystal quasi parallel to its atomic axes or planes.** In dependence on the crystal alignment along either planes or atomic strings channeling can be divided into

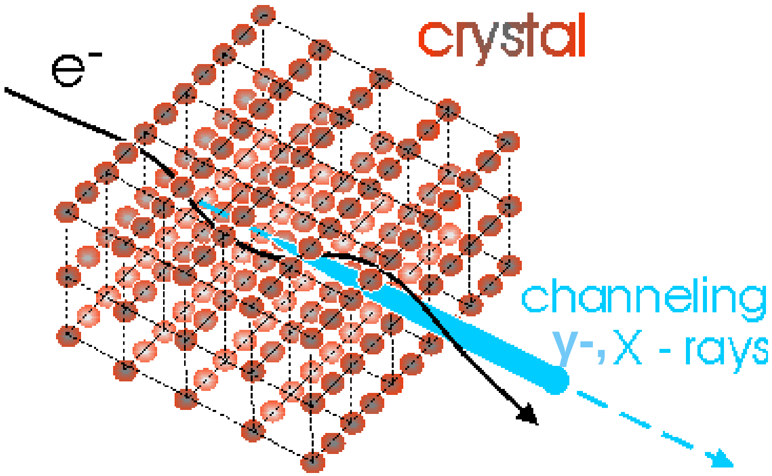
- ***Planar*** **channeling**
- ***Axial*** **channeling**

Planar/Axial field $10^9/10^{11}$ V/cm

*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

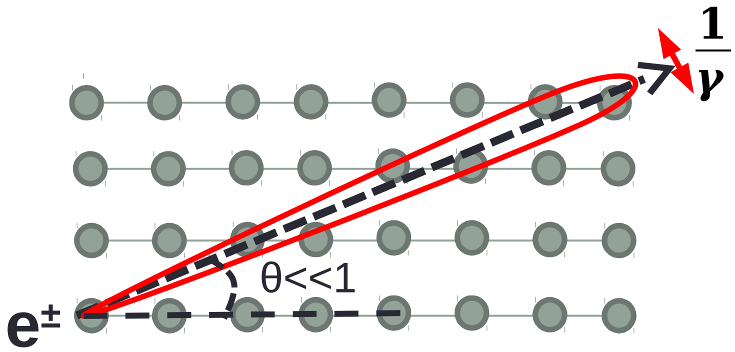
Coherent effects in a crystal

Channeling radiation*

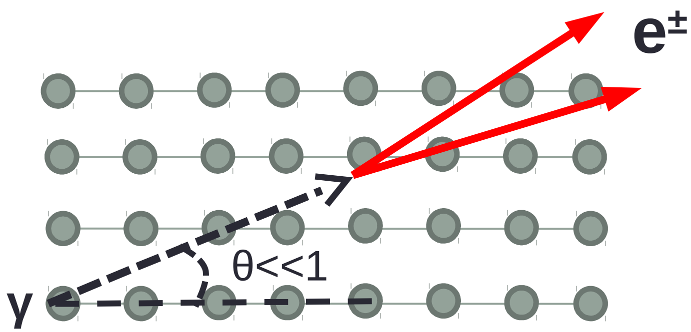


Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

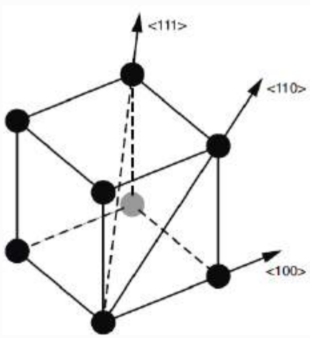


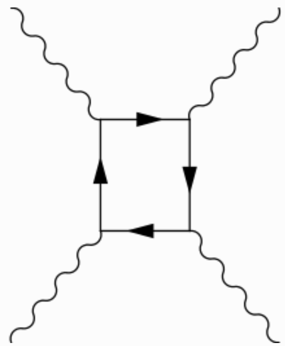
*M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
**B. Ferretti, Nuovo Cimento 7, 118 (1950).
**M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
*** H. Überall, Phys. Rev. 103, 1055 (1956).

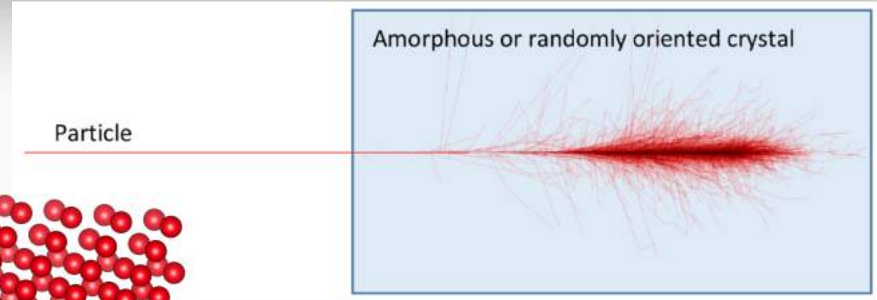
Electromagnetic shower acceleration

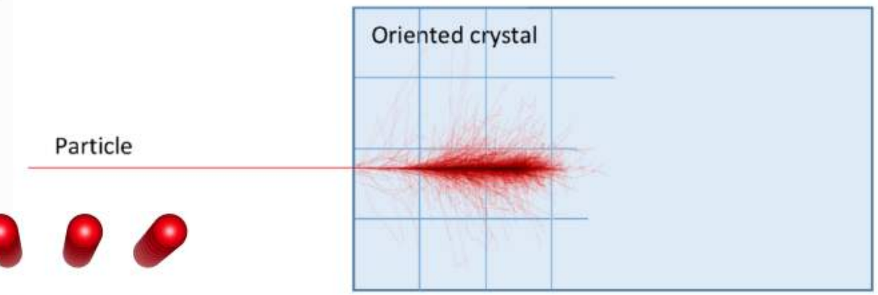
Axial field
10^{11} V/cm

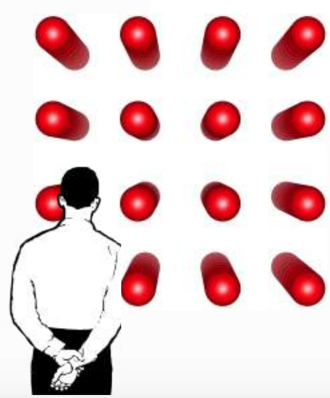
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**









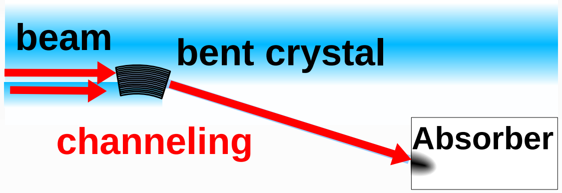


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

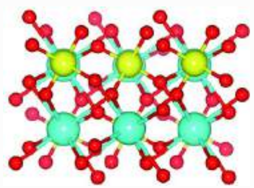
Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced.

Applications*

Crystal-based collimation or beam extraction from an accelerator

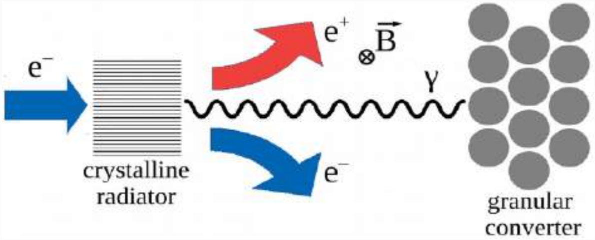


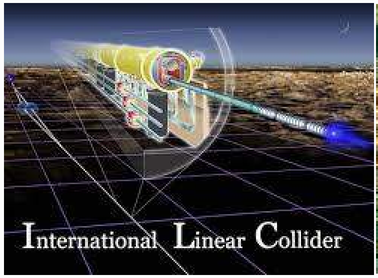
Ultrashort crystalline calorimeter

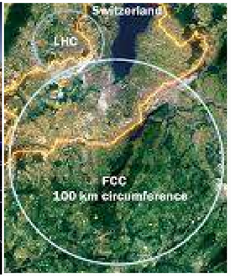


Gamma-ray Space Telescope

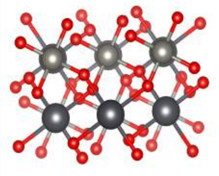
Positron source for future e+/e- and muon colliders



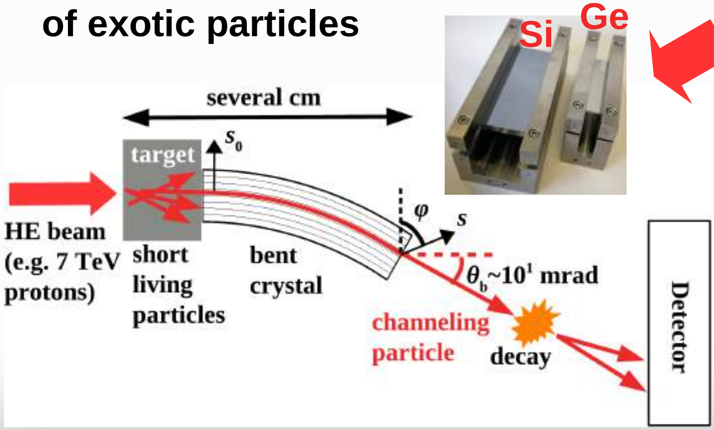




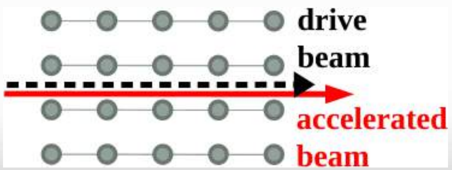
Oriented crystals



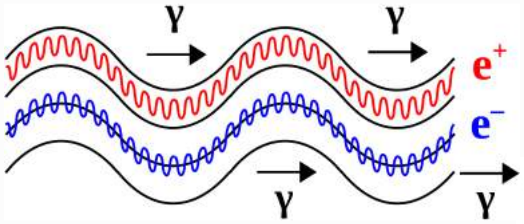
Measurement of dipole magnetic and electric moments of exotic particles

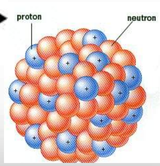


Plasma acceleration



X and γ-ray source for nuclear and medical physics

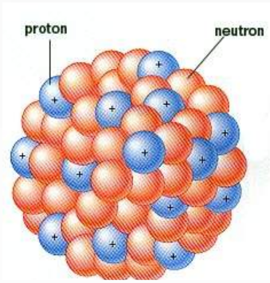




*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

Applications of oriented crystals*

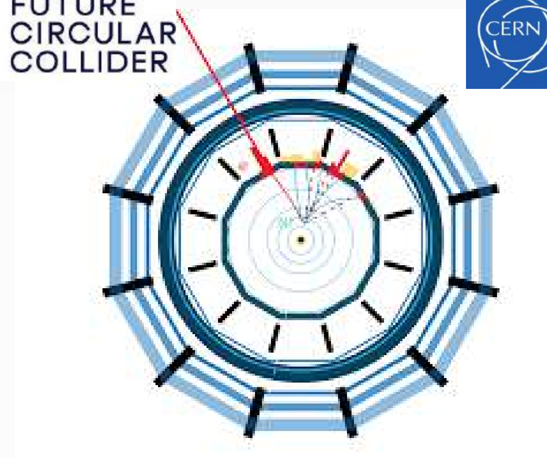
X and γ-ray source for nuclear physics and cancer radiotherapy



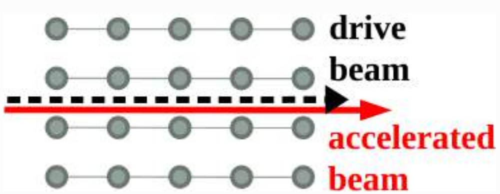
Gamma-ray Space Telescope

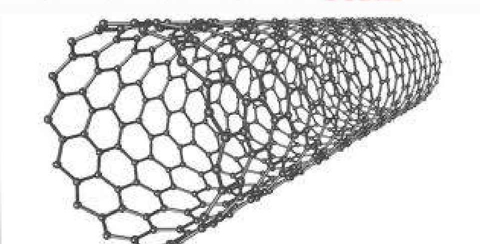
Positron source for future multi-billion € e+/e- and muon colliders

FUTURE CIRCULAR COLLIDER

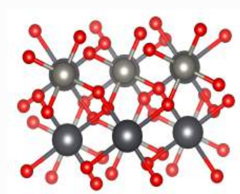


Plasma wakefield acceleration





Oriented crystals



Crystal-based beam extraction from accelerators and colliders

Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2025, Project TRILLION GA n. 101032975

Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples to bring them to a large scientific and industrial community and under a free Geant4 license.

Group:

- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

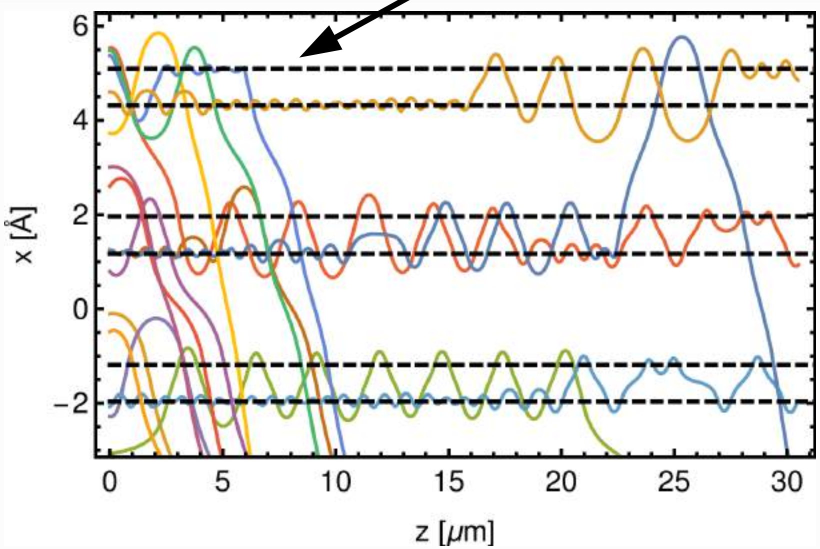
Location:

- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Baseline channeling simulation technique: CRYSTALRAD Monte Carlo simulation code

Main conception – simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single **scattering simulation** at every step

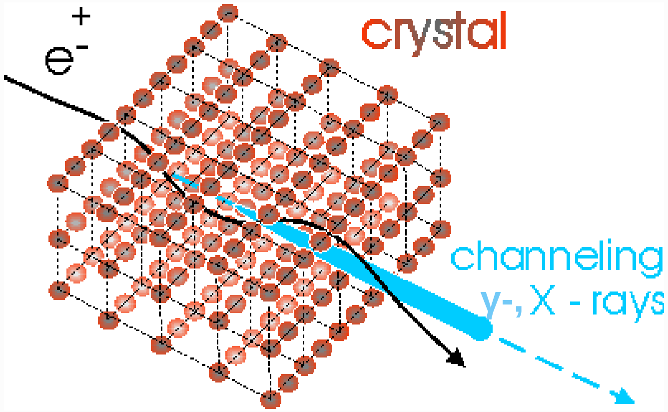
Crystal planes



channeling*

Advantages:

- High calculation speed
- **MPI** parallelization for high performance computing



Baier-Katkov formula:
integration is made over the classical trajectory

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)
***A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)**
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

GEANT4

A SIMULATION TOOLKIT

How to implement an external code into Geant4? Geant4 FastSim interface, a solution of most of challenges

FastSim model:

- **Physics list independent**
- Declared in the **DetectorConstruction** (just **few lines of code**)
- Is activated **only** in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** at the step of FastSim model and then resumes them

```
G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4Proton::ProtonDefinition()||
    &particleType == G4AntiProton::AntiProtonDefinition()||
    &particleType == G4Electron::ElectronDefinition() ||
    &particleType == G4Positron::PositronDefinition();// ||
    //&particleType == G4Gamma::GammaDefinition();
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
{
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

void TestModel::DoIt(const G4FastTrack& fastTrack,
                     G4FastStep& fastStep)
{
```

Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

How to use the Geant4 channeling model in your example?

- **Add to DetectorConstruction::Construct()**

```
//crystal volume
G4Box* crystalSolid = new G4Box("Crystal",CrystalSizeX/2,CrystalSizeY/2,CrystalSizeZ/2.);
crystalLogic = new G4LogicalVolume(crystalSolid,crystalMaterial,"Crystal");
            new G4PVPlacement(xRot,posCrystal,crystalLogic,"Crystal",logicWorld,false,0);
//crystal region (necessary for the FastSim model)
fRegion = new G4Region("Crystal");
fRegion->AddRootLogicalVolume(crystalLogic);
```

Volume declaration (completely standard)

G4Region declaration

- **Add to DetectorConstruction::ConstructSDandField()**

```
void DetectorConstruction::ConstructSDandField()
{
    // --------------- fast simulation ----------------------------
    //extract the region of the crystal from the store
    G4RegionStore* regionStore = G4RegionStore::GetInstance();
    G4Region* RegionCh = regionStore->GetRegion("Crystal");

    //create the channeling model for this region
    G4ChannelingFastSimModel* ChannelingModel =
        new G4ChannelingFastSimModel("ChannelingModel", RegionCh);
    //activate the channeling model
    ChannelingModel->Input(crystalMaterial, Lattice);
    //setting bending angle of the crystal planes (default is 0)
    ChannelingModel->GetCrystalData()->
            SetBendingAngle(BendingAngle,crystalLogic);

    //activate radiation model
    if (ActivateRadiationModel) ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim model declaration

Model activation and input

Optional

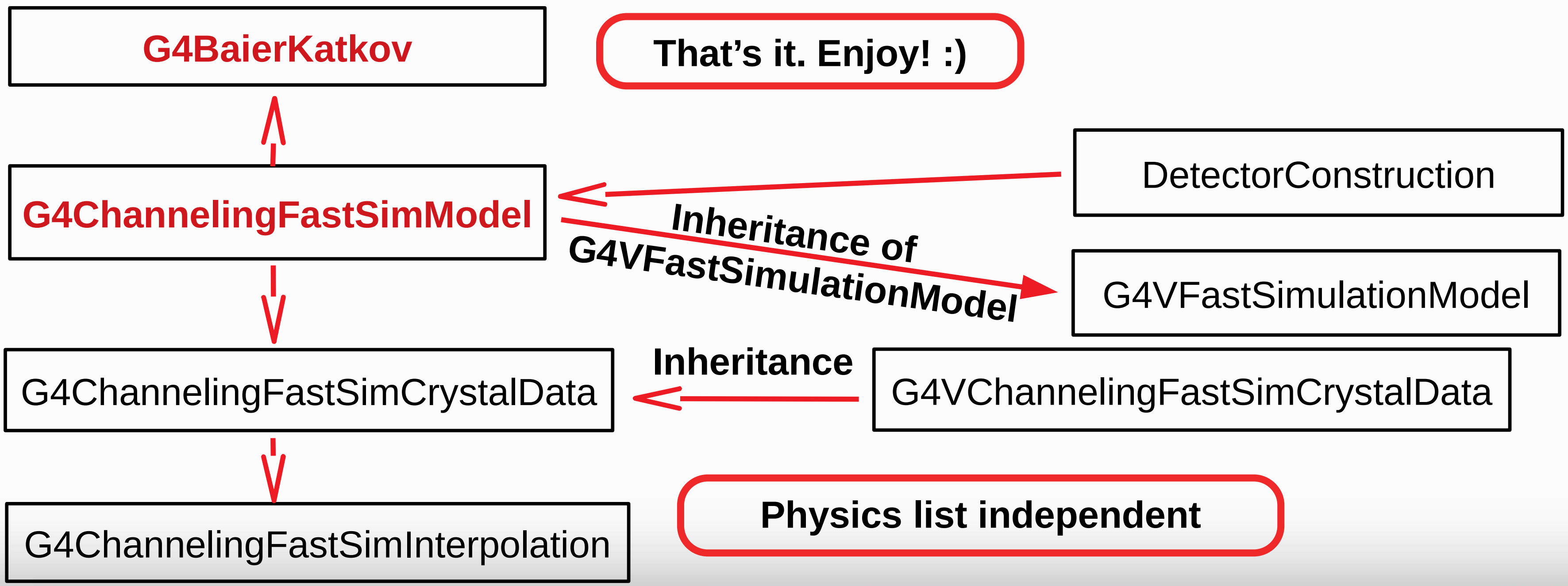
Radiation model activation

How to use the Geant4 channeling model in your example?

- **Add to main:**

Register FastSimulationPhysics

```
G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics();
fastSimulationPhysics->BeVerbose();
// -- activation of fast simulation for particles having fast simulation models
// -- attached in the mass geometry:
fastSimulationPhysics->ActivateFastSimulation("e-");
fastSimulationPhysics->ActivateFastSimulation("e+");
// -- Attach the fast simulation physics constructor to the physics list:
physicsList->RegisterPhysics( fastSimulationPhysics );
```



Current status

Already in geant4-11.2.0 !

geant4-v11.2.0/source/parameterisations/channeling/

Please use it!

Release December 8, 2023 https://geant4.web.cern.ch/download/11.2.0.html

Don't hesitate to contact me in the case of any problems/issues/suggestions

sytov@fe.infn.it

Geant4 Physics Reference Manual:

https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/solidstate/channeling/channeling_fastsim.html

Please cite our papers if you use our model:

1. A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)
2. A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Our project MIRACLE, no. HP10BIW7VR
Cineca ISCRA Class B National Italian project

MIRACLE
Medical physIcs and RAdiation in Crystals simuLation with gEant4
Main goal: to supply **Italian Geant4 community** and their international collaborators by CINECA HPC resources necessary to accomplish **MC_INFN** and **TRILLION** projects.
25/10/2021 - 25/01/2023

Marconi 100: 0.992 Mh for 1 year

Galileo 100: 2.4 Mh for 1 year

Italian organizations involved
- INFN Sezione di Catania
- INFN Sezione di Ferrara
- INFN Laboratori Nazionali del Sud
- INFN Napoli
- INFN Roma1
- Istituto Superiore di Sanità
- University of Messina
- University of Napoli

Foreign organizations involved
- ELI-Beamlines, Institute of Physics, (FZU), Czech Academy of Sciences
- Institute for Nuclear Problems, Belarusian State University
- University of Surrey

PI A. Sytov

Korea National Supercomputing Center, KISTI
KSC-2022-CHA-0003

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supercomputer
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Multithreading works!
Checked at the supercomputer
Galileo100@CINECA (Italy)
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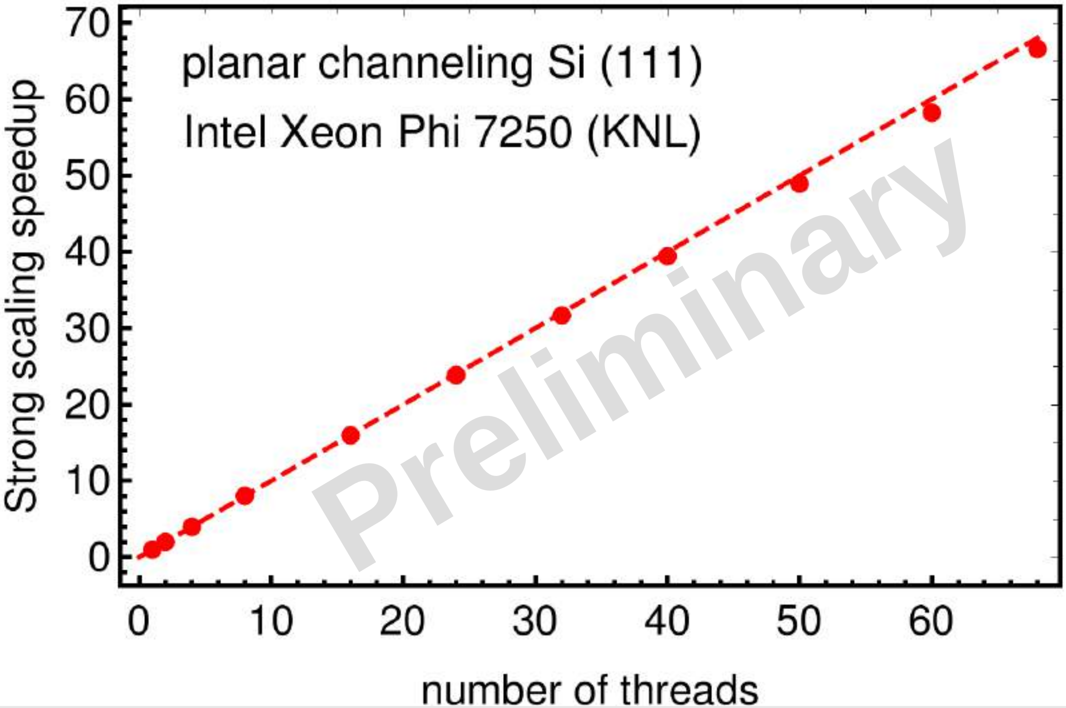
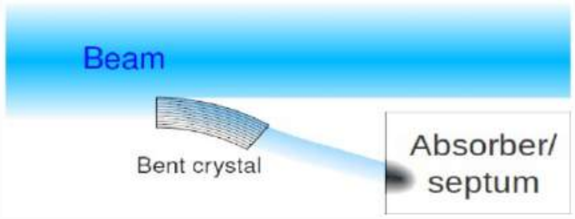
Geant4 channeling model scaling on Nurion



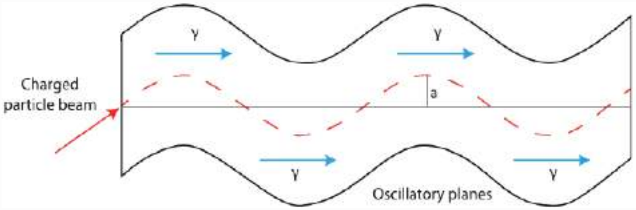
Marie Sklodowska-Curie Action Global Fellowships by A. Sytov in 2021-2024, Project TRILLION

Specific applications to implement into Geant4:

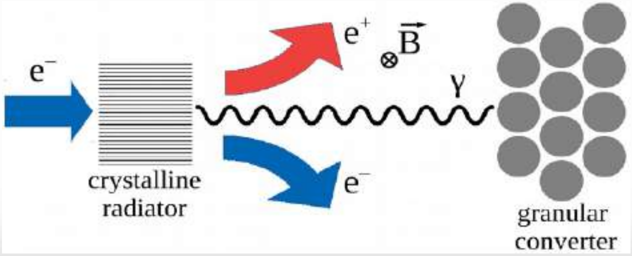
- **Crystalline deflector to extract a charged particle beam from an accelerator** (electron synchrotron, hadron collider) to supply fixed-target experiments by an intense low-emittance beam.



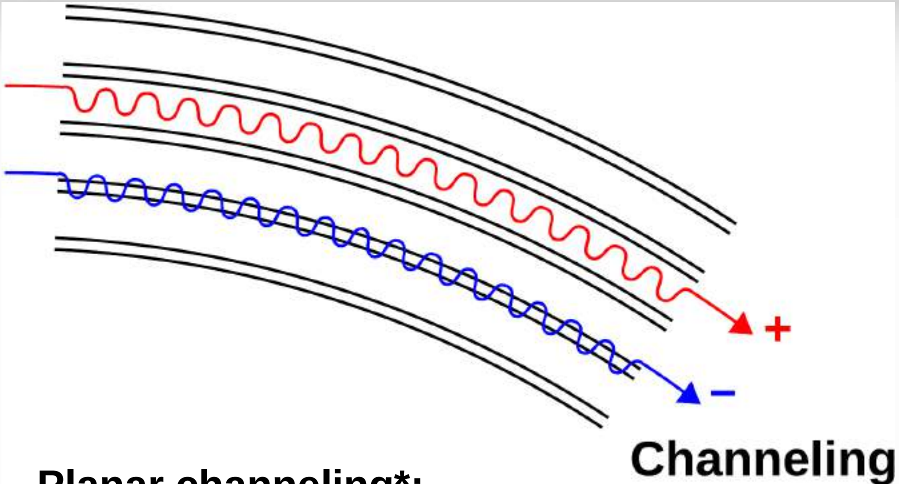
- **Crystalline source of hard X-ray and gamma radiation, crystalline undulator (CU)**.



- **Crystal-based hybrid positron source** for both linear and circular e+e- colliders (**ILC**, **FCC-ee**) as well as for **muon colliders**.



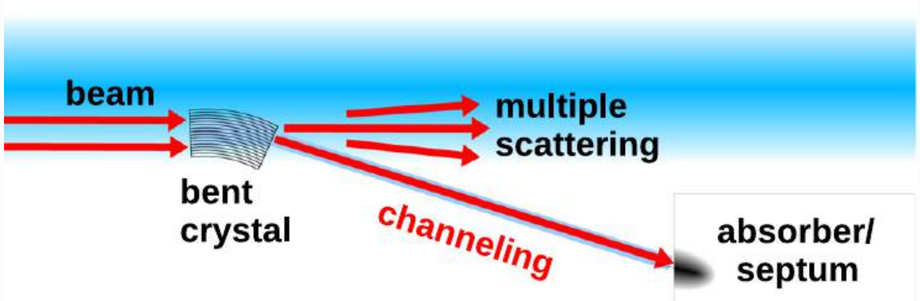
Crystal-based extraction



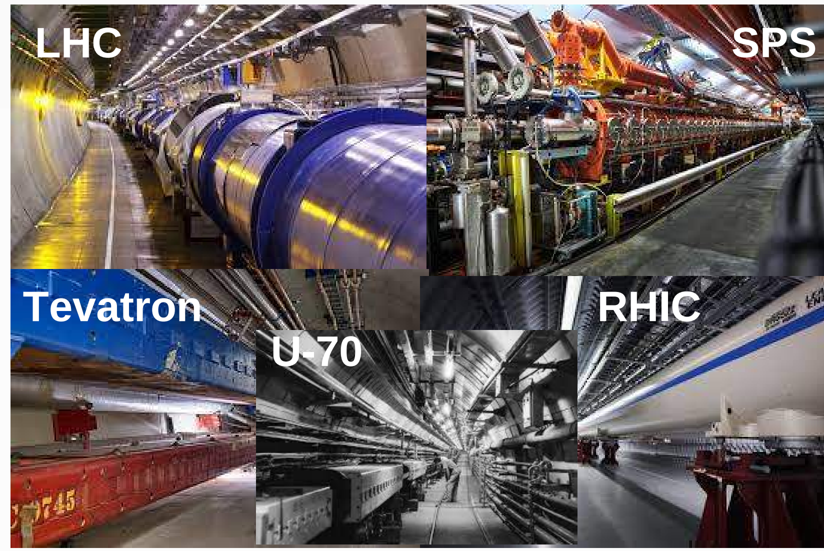
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

Crystal-based extraction/collimation



Crystal-based collimation and **extraction have been used at hadron machines**

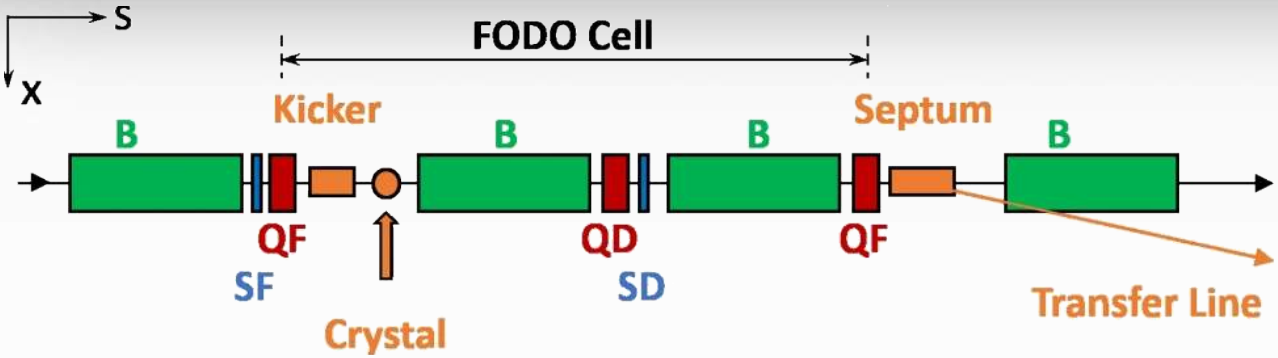


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

Interesting for tens of electron synchrotrons

*J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)
E.N. Tsyganov, Fermilab TM-682 (1976)
A. Sytov et al. Eur. Phys. J. C 82, 197 (2022)

Crystal-based extraction: possible setup at DESY-II

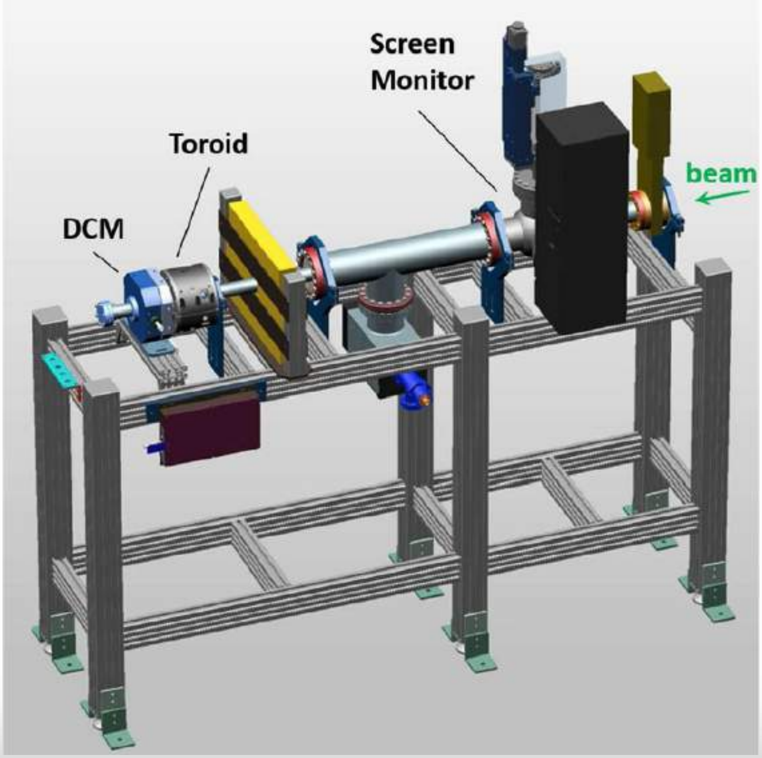


B->dipoles
QF/QD->focusing/ defocusing quadrupoles

6 GeV electrons

Advantages:

- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- **Few GeV** electron beam, **typical for synchrotron light sources** existing in the world.



Applications:

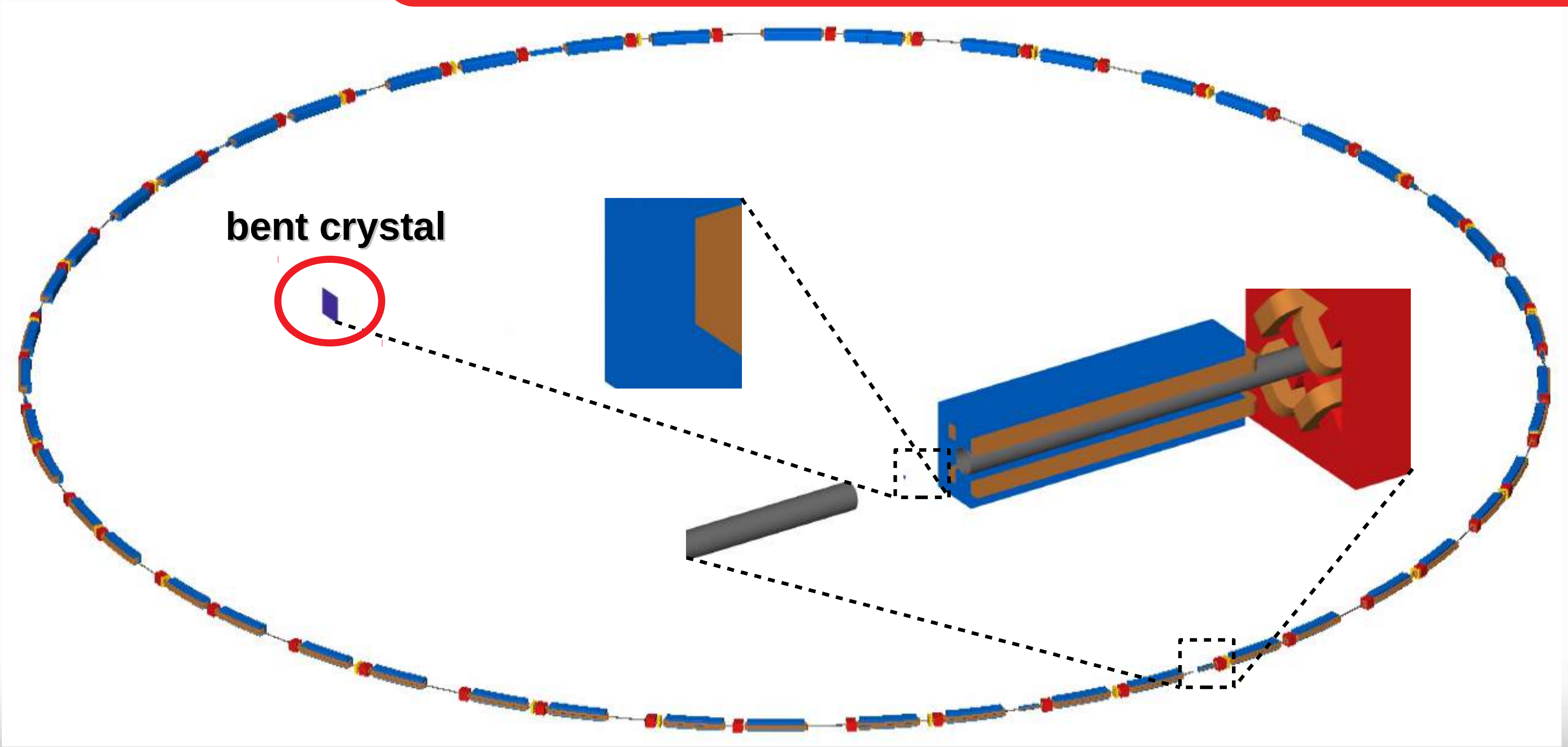
- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)

A. Sytov, G. Kube et al. Eur. Phys. J. C 82, 197 (2022)

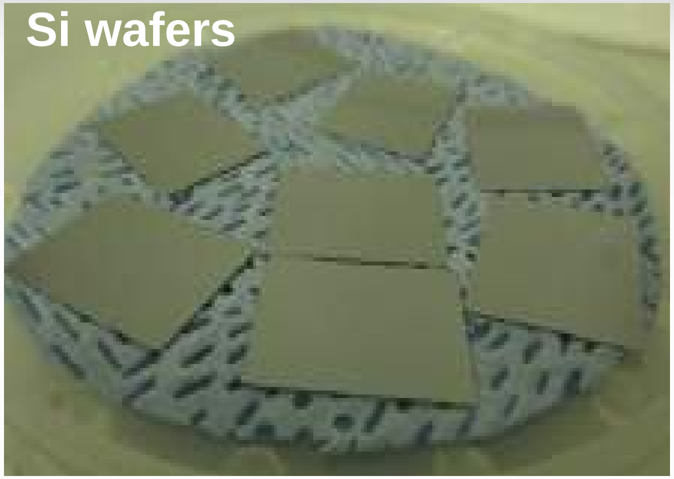
My mission to DESY:
full simulations with the BDSim simulation code

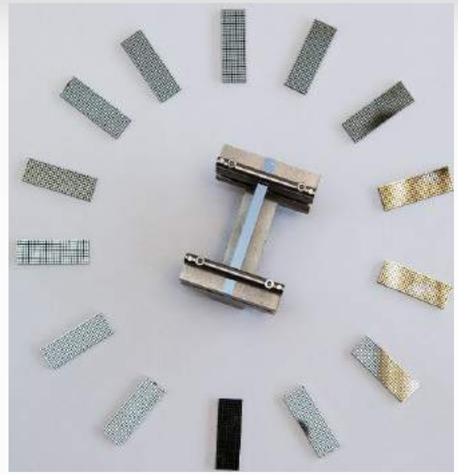
Beam Delivery Simulation

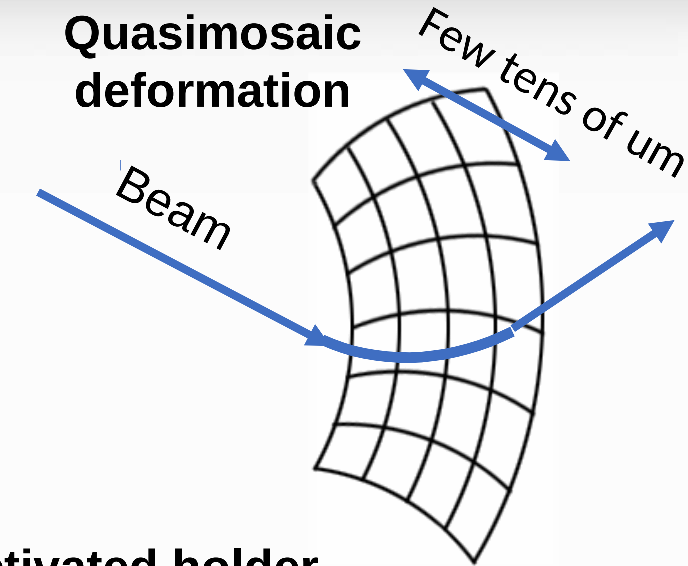
Purpose of BDSIM:
Beam Delivery Simulation (BDSIM) is a C++ program that utilises the **Geant4 toolkit** to simulate both the **transport of particles in an accelerator** and their **interaction with the accelerator material**. BDSIM is capable of **simulating a wide variety of accelerator components and magnets** with Geant4 geometry dynamically built based on a text input file. **Thick lens accelerator** tracking routines are provided for fast accurate tracking in a vacuum.

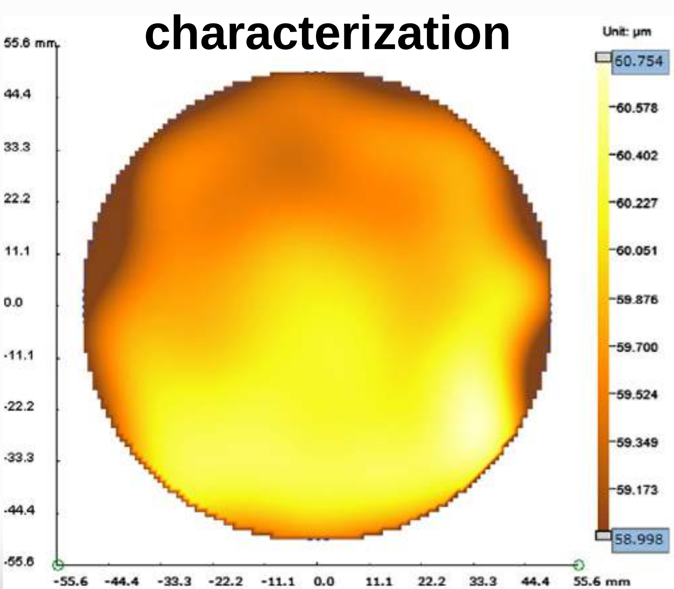


Manufacturing and characterization of bent silicon crystals @INFN Ferrara

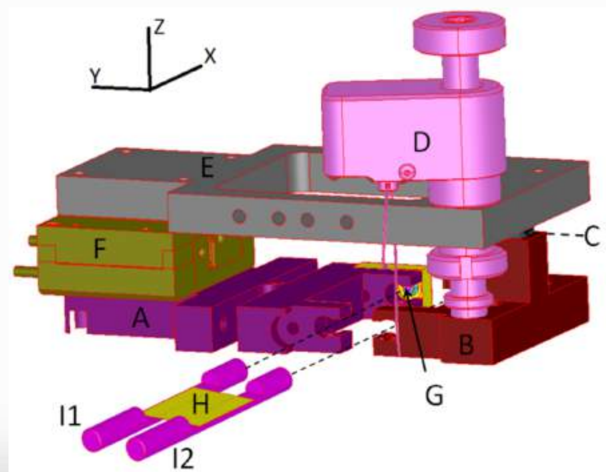


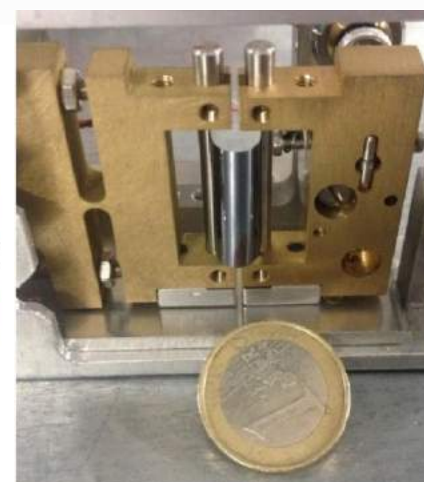






Piezo-activated holder





Implementation of a new component and a new physics list

```cpp
#include "BDSIMClass.hh" // bdsim interface

#include "CrystalDeflector.hh"
#include "CrystalDeflectorConstructor.hh"

#include "FTFP_BERT.hh"
#include "G4FastSimulationPhysics.hh"
#include "G4StepLimiterPhysics.hh"
#include <iostream>

int main(int argc, char** argv)
{
  // construct an instance of bdsim
  BDSIM* bds = new BDSIM();

  // Physics list
  G4VModularPhysicsList* physicsList = new FTFP_BERT;
  // -- Create helper tool, used to activate the fast simulation:
  G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics();
  fastSimulationPhysics->BeVerbose();
  // -- activation of fast simulation for particles having fast simulation models
  // -- attached in the mass geometry:
  fastSimulationPhysics->ActivateFastSimulation("e-");
  fastSimulationPhysics->ActivateFastSimulation("e+");
  // -- Attach the fast simulation physics constructor to the physics list:
  physicsList->RegisterPhysics( fastSimulationPhysics );
  physicsList->RegisterPhysics(new G4StepLimiterPhysics());
  bds->RegisterUserPhysicsList(physicsList);

  // register a custom component by name udipole with a user-provided constructor
  // BDSIM will delete the constructor at the end.
  bds->RegisterUserComponent("crystaldeflector", new CrystalDeflectorConstructor());

  // construct geometry and physics
  bds->Initialise(argc, argv);
  if (!bds->Initialised()) // check if there was a problem.
    {std::cout << "Intialisation failed" << std::endl; return 1;}

  bds->BeamOn(); // run the simulation
  delete bds;    // clean up
  return 0;      // exit nicely
}
```

CrystalDeflectorConstructor.cc

```cpp
BDSAcceleratorComponent* crystal = new CrystalDeflector(element->name,
                                                        element->l*CLHEP::m,
                                                        element->xsize*CLHEP::m,
                                                        element->ysize*CLHEP::m,
                                                        element->materialThickness*CLHEP::m,
                                                        element->axisX,
                                                        element->axisY,
                                                        element->axisZ,
                                                        horizontalWidth*CLHEP::m,
                                                        bendingAngle,
                                                        material,
                                                        vacuumMaterial,
                                                        crystalLattice,
                                                        region,
                                                        colour,
                                                        radiationModel);
```

```
D12H: drift, l=0.4125;
CR1: usercomponent, userTypeName="crystaldeflector",
l=0.4125, xsize=1*cm, ysize=1*cm,
materialThickness=0.175*mm, offsetX=-1.126046*cm,
offsetY=0*mm, axisX=0.000, axisY = -0.00097, axisZ = 0.,
horizontalWidth=1*m,  material="G4_Si",
vacuumMaterial="vacuum",
userParameters="crystalRegion:crystal1
crystalBendingAngle:0.00175 crystalLattice:(111)
colour:decapole radiationModel:false"; dump1: dump,
l=1*mm, horizontalWidth=4*cm,
apertureType="rectangular",offsetX=2.98*cm;
D18: drift, l=0.495;
```

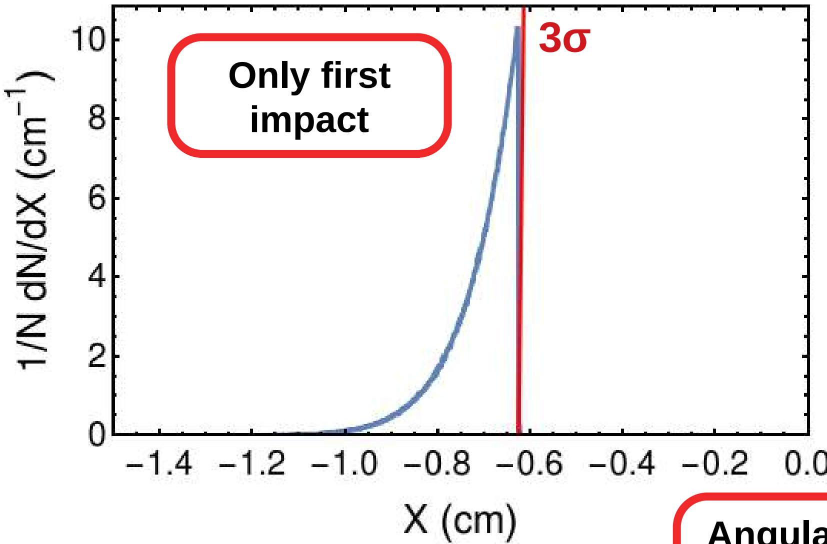
CrystalDeflectorConstructor.cc

```
void CrystalDeflector::BuildCrystal()
{
    //build crystal solid
    G4Box* crystalSolid = new G4Box(name + "_crystal_solid",
                crystalXSize * 0.5,
                crystalYSize * 0.5,
                crystalMaterialThickness * 0.5);
    RegisterSolid(crystalSolid); // for deletion by bdsim

    // make a logical volume for the crystal
    G4LogicalVolume* crystalLV = new G4LogicalVolume(crystalSolid,
                      crystalMaterial,
                      name + "_crystal_lv");

    // visualisation attributes - make it nicely visible
    G4VisAttributes* crystalVis = new G4VisAttributes(*BDSColours::Instance()->GetColour(crystalcolour));
    crystalVis->SetVisibility(true);
    crystalLV->SetVisAttributes(crystalVis);
    RegisterVisAttributes(crystalVis);// for deletion by bdsim
    RegisterLogicalVolume(crystalLV); // for deletion by bdsim

    G4RotationMatrix* crystalRM = new G4RotationMatrix();
    crystalRM->rotateX(crystalAxisX);
    crystalRM->rotateY(crystalAxisY);
    crystalRM->rotateZ(crystalAxisZ);
    RegisterRotationMatrix(crystalRM); // for deletion by bdsim
    G4double crystalZPos = 0*CLHEP::cm;
    G4ThreeVector crystalPos = G4ThreeVector(0,0, crystalZPos);
```

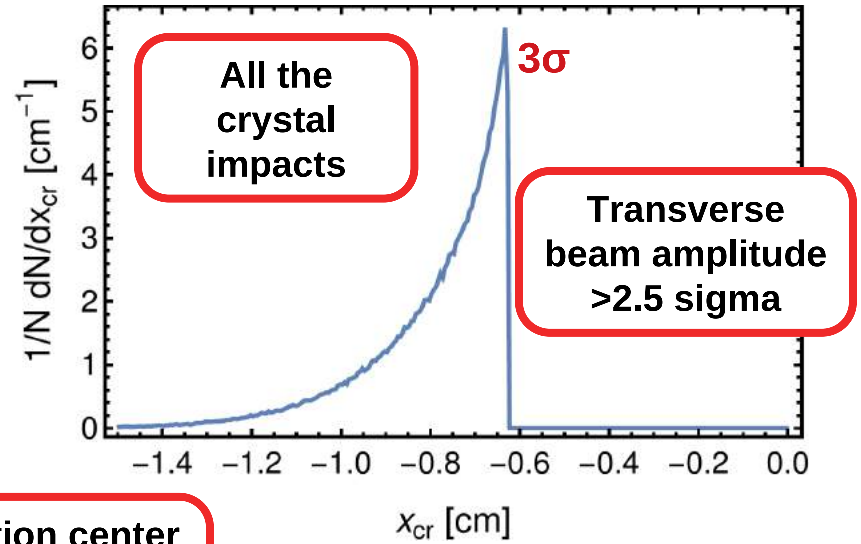
```
//physical volume
auto crystalPV = new G4PVPlacement(crystalRM,
                crystalPos,
                crystalLV,
                name + "_crystal",
                containerLogicalVolume,
                false,
                0,
                checkOverlaps);
RegisterPhysicalVolume(crystalPV); // for deletion by bdsim

G4Region* crystalRegion = new G4Region(crystalRegionName);
crystalRegion->AddRootLogicalVolume(crystalLV);

//create the channeling model for this region
G4ChannelingFastSimModel* ChannelingModel = new G4ChannelingFastSimModel("ChannelingModel", crystalRegion);
//activate the channeling model
ChannelingModel->Input(crystalMaterial, crystalLattice);
//setting bending angle of the crystal planes (default is 0)
ChannelingModel->GetCrystalData()->SetBendingAngle(crystalBendingAngle,crystalLV);

if(crystalRadiationModel){ChannelingModel->RadiationModelActivate();}
```

Crystal impact
(both transverse and energy spread is taken into account)

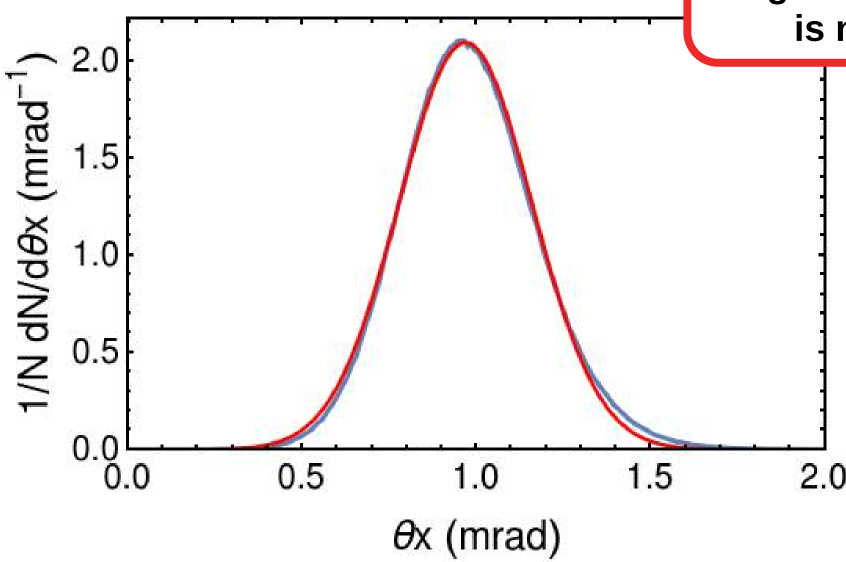
Old paper*

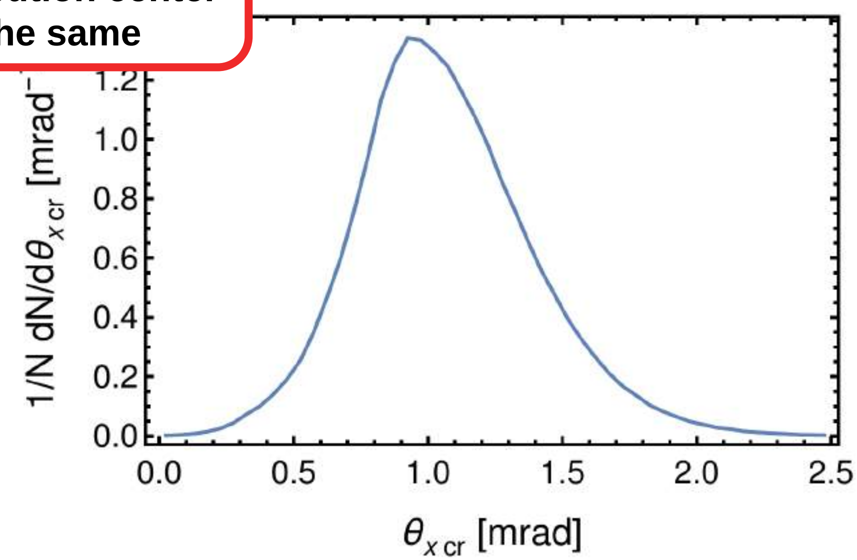


BDSim



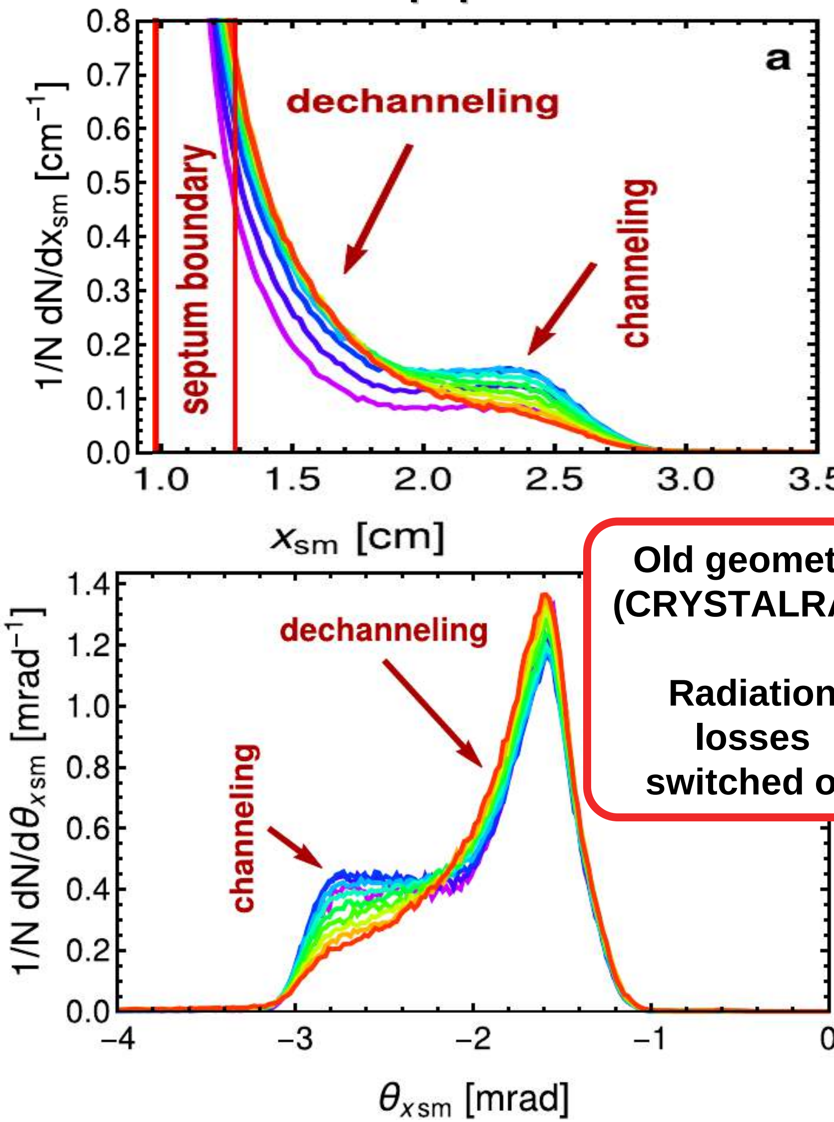
Angular distribution center is nearly the same





Crystal-based extraction: simulation results distributions at the septum magnet entrance

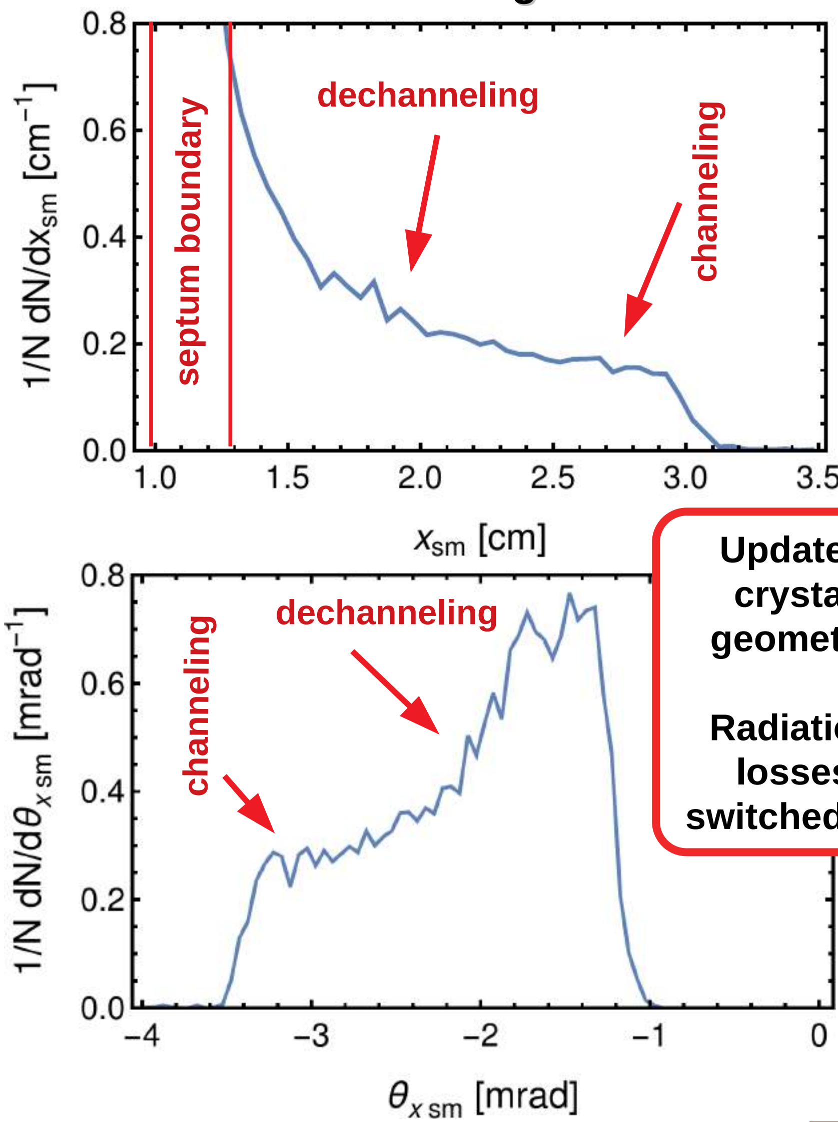
Old paper*



Old geometry (CRYSTALRAD)

Radiation losses switched on

BDSim & ChannelingFastSimModel



Updated crystal geometry

Radiation losses switched off

Summary and Future plans 2024

parameters* (still valid)

Bent crystal thickness	175 µm
Bent crystal bending angle	1.75 mrad
Bent crystal transverse position	−0.63 cm
Bent crystal angular alignment	0.97 mrad
Septum magnet transverse position	0.98 cm

Main part of the **beam** will **not touch** the **crystal**

5% of the **beam will enter** into the **septum magnet**

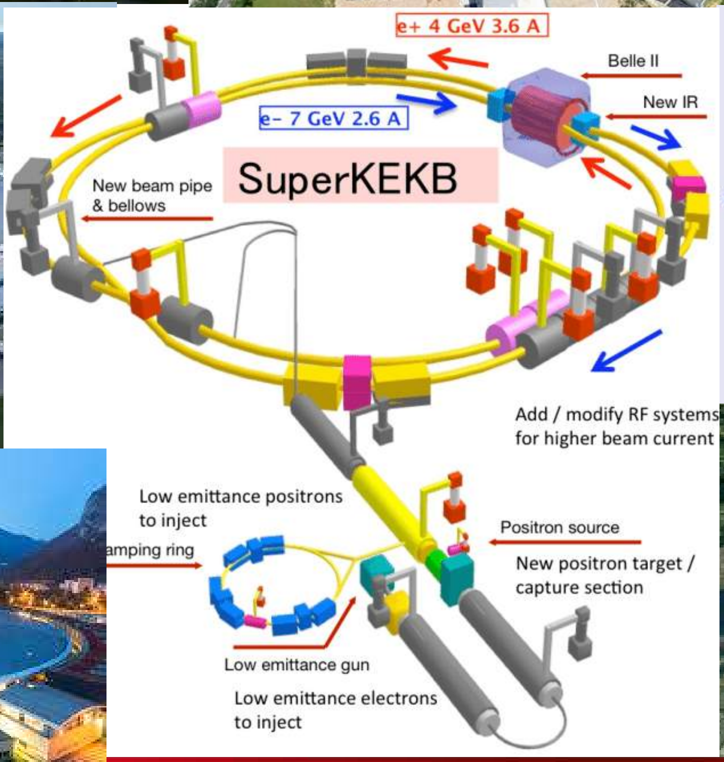
~50 pC can be extracted

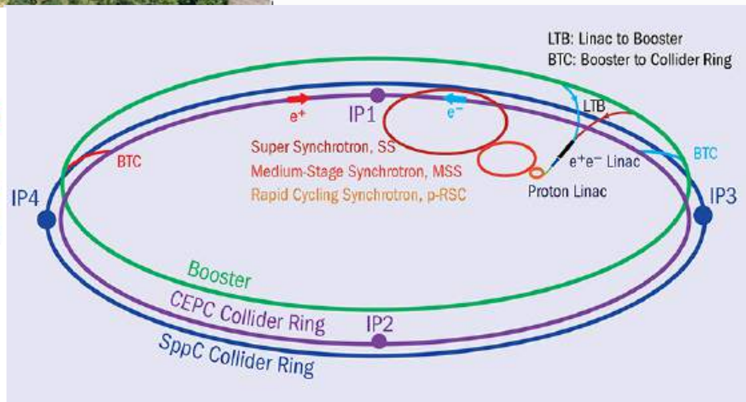
Future plans

- **Turn on cavities** and **radiation losses** in the **crystal**
- **Track** the particles also in the **extraction line**
- Calculate the **beam emittance** and **beam charge** at the extraction line exit
- Simulation of **ionization losses** in the crystal to estimate the radiation damage if any
- Further **optimization** of the crystal geometry and location
- Consider **other crystal materials/crystalline effects**

*A. Sytov, G. Kube et al. Eur. Phys. J. C 82, 197 (2022)

Where the crystal-based extraction of electrons can be applied?

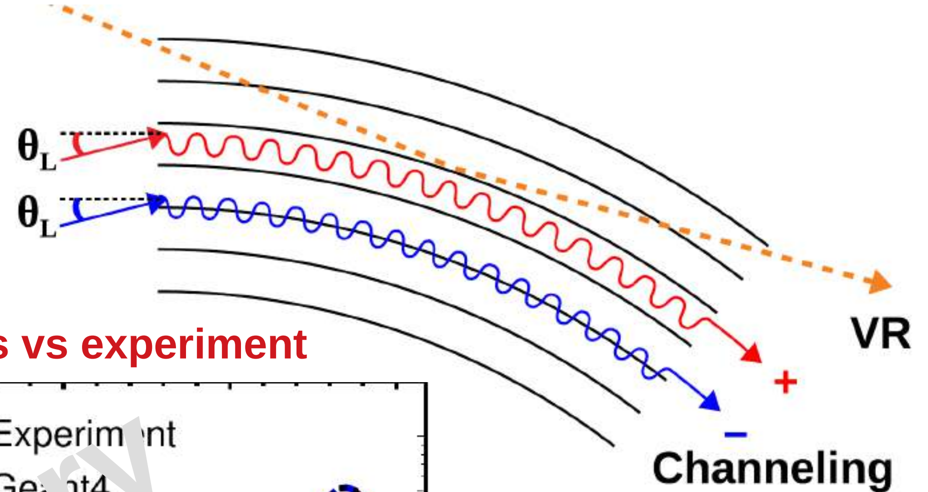




More Geant4 channeling model validation: quasichanneling oscillations* at SLAC FACET Facility

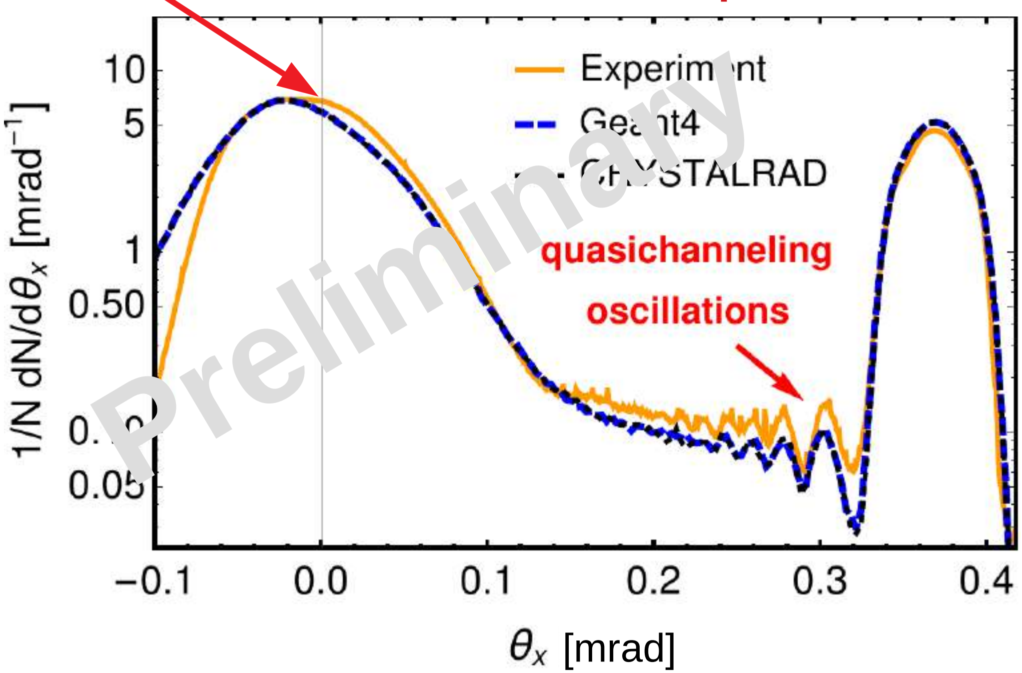
20.35 GeV positrons

60 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



quasichanneling oscillations

channeling

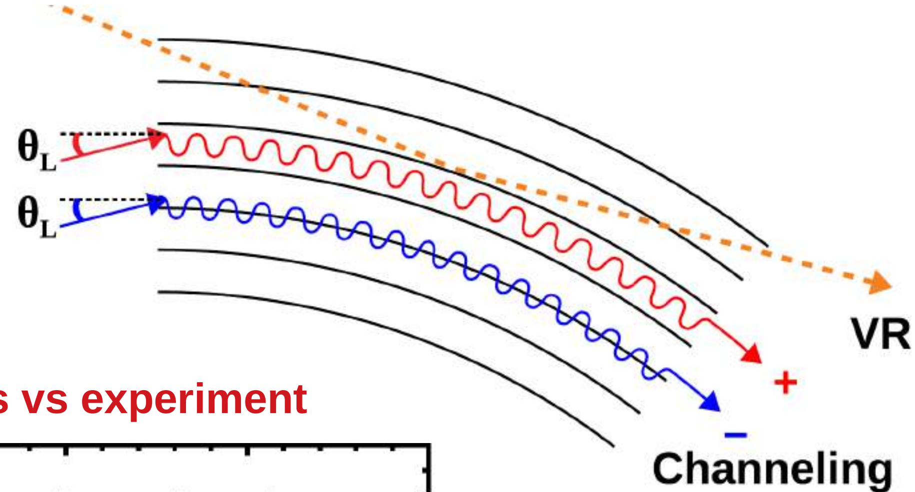
To be submitted for publication soon

*T. N. Wistisen, …, and A. Sytov, Phys. Rev. Lett. 119, 024801 (2017)

Geant4 channeling model validation: beam deflection by a bent crystal

855 MeV electrons

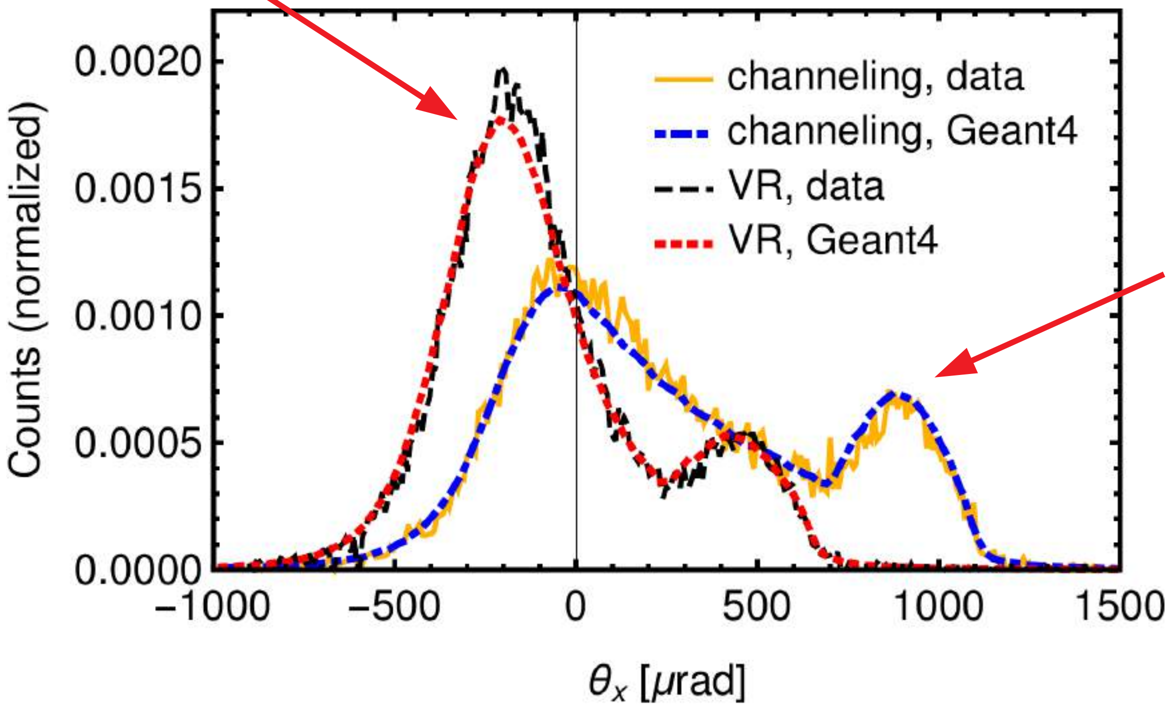
15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment

channeling



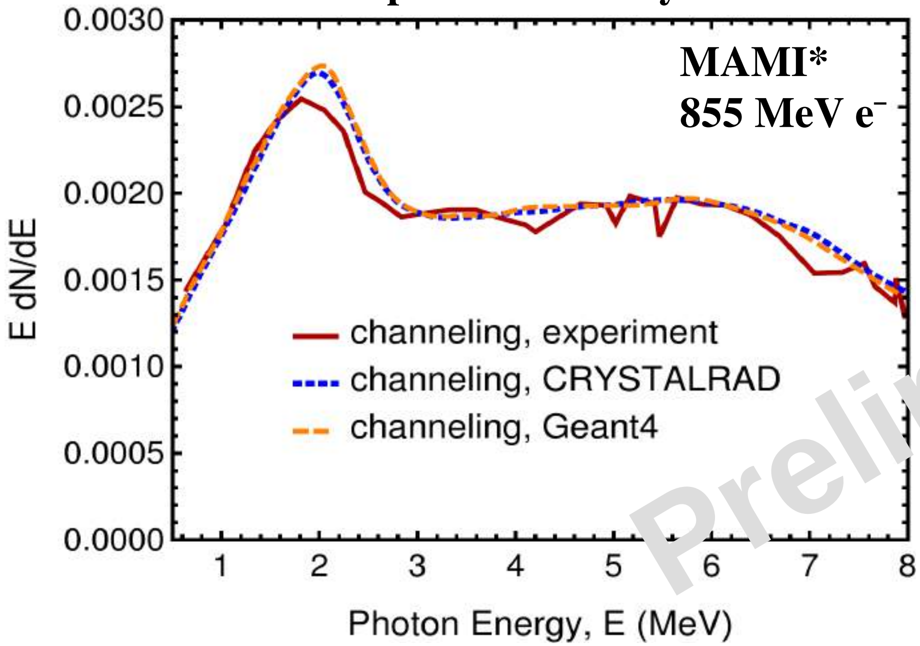
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

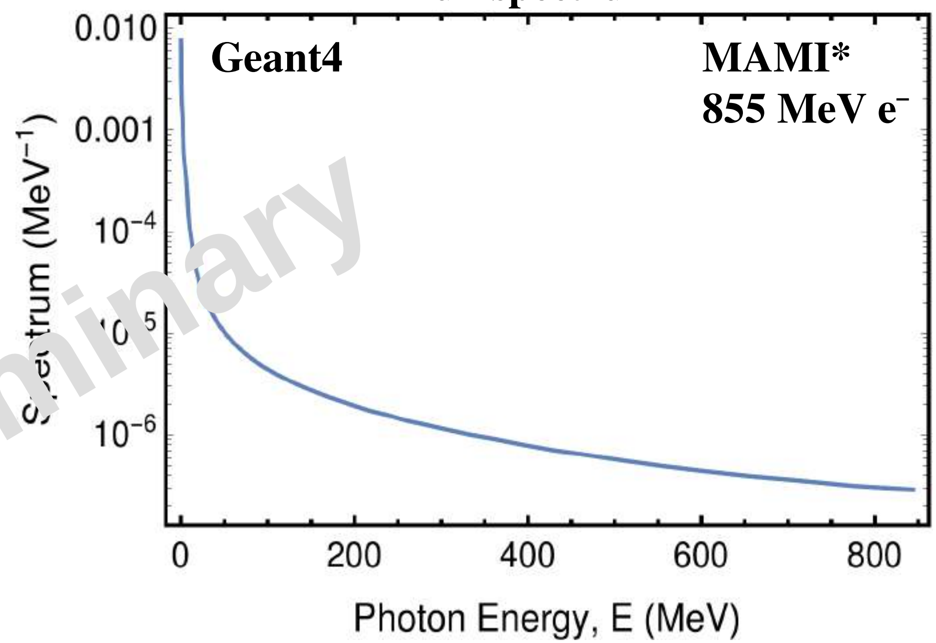
- **Physics list independent**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations

Spectral intensity



Full spectrum

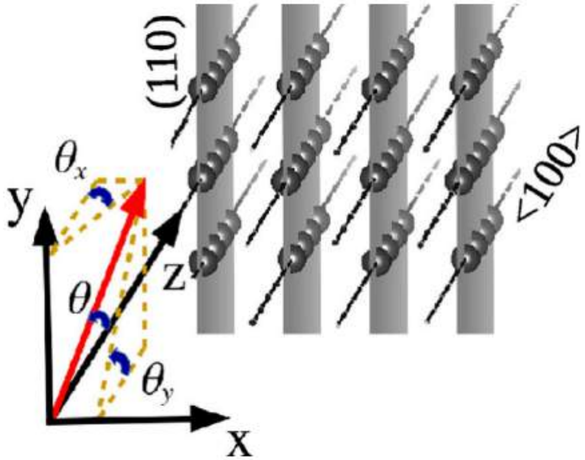


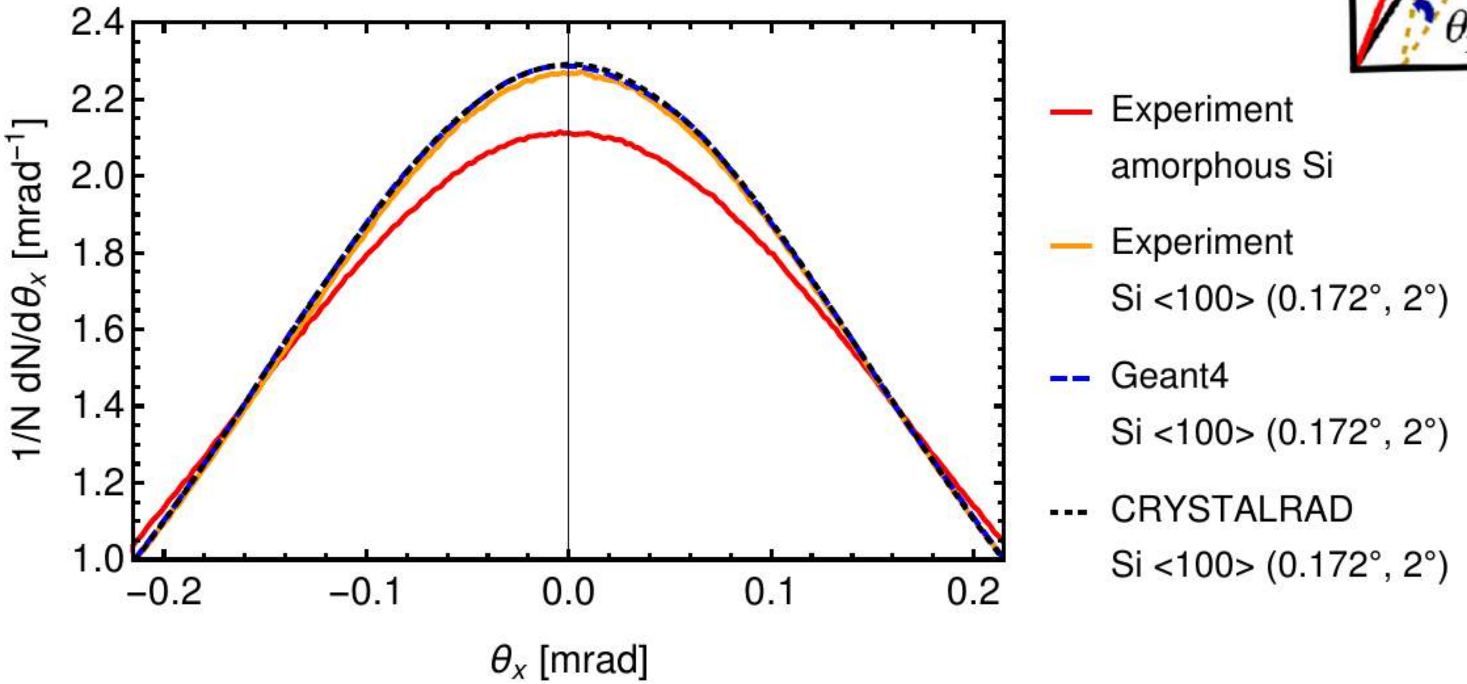
To be submitted for publication soon

*L. Bandiera et al. Phys. Rev. Lett. 115, 025504 (2015)

2D Geant4 channeling model validation: coherent scattering suppression effect*

Multiple scattering in crystal and multiple scattering in amorphous material are different!

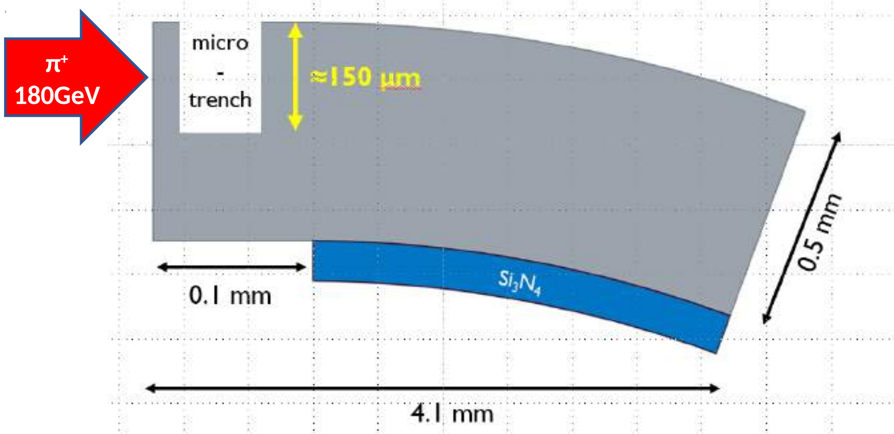


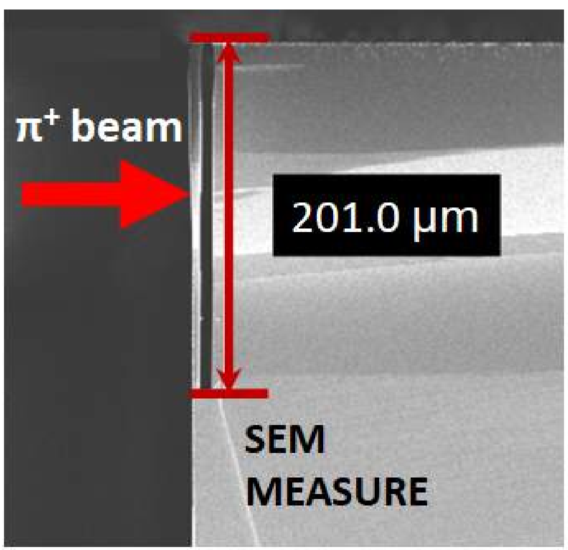


To be submitted for publication soon

***A. Mazzolari, A. Sytov et al. Eur. Phys. J. C 80, 63 (2020)**

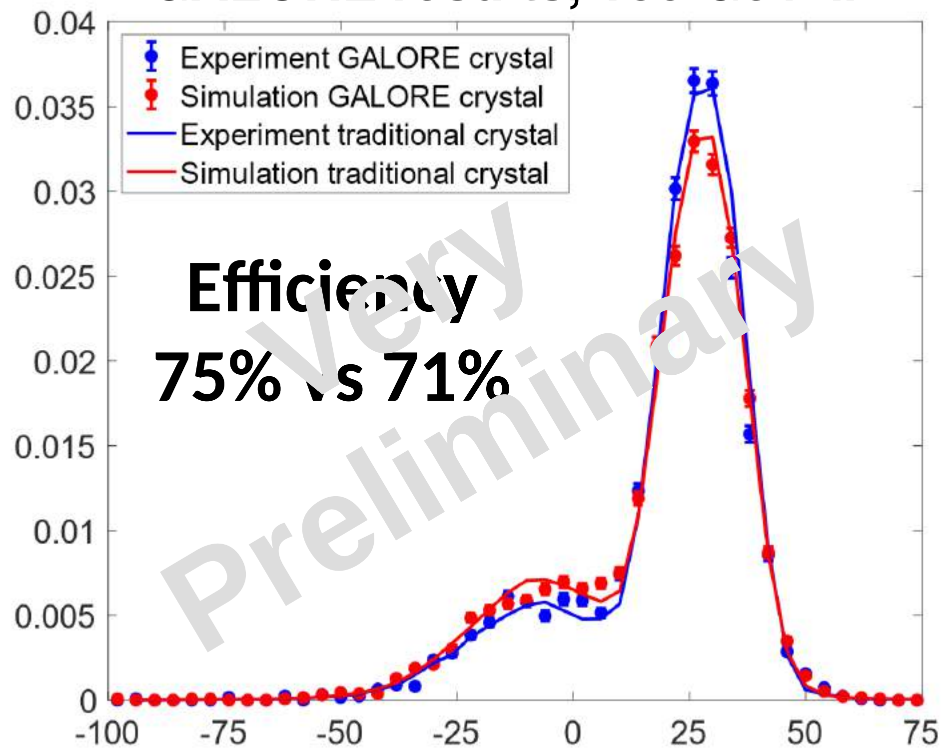
Geant4 simulations of the experiment GALORE: Crystalline cut to drastically increase the channeling efficiency





Geant4 simulations vs experimental data

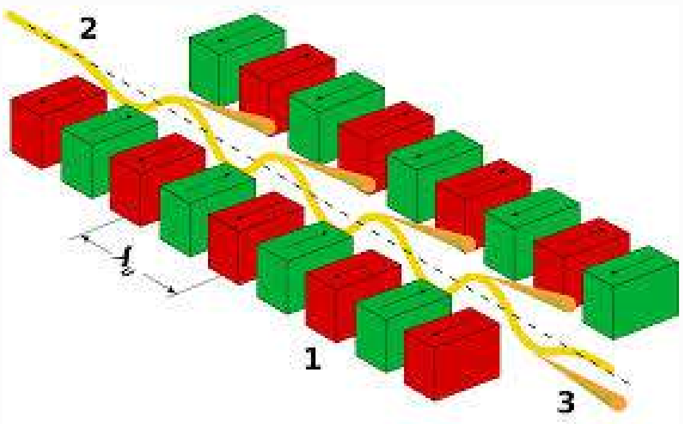
GALORE results, 180 GeV π+



M. Romagnoni, ..., A. Sytov et al. Crystals 12 (9), 1263 (2022)
M. Romagnoni, ..., A. Sytov et al. Eur. Phys. J. D 76, 135 (2022).

Channeling radiation in a bent crystal: Crystalline undulator

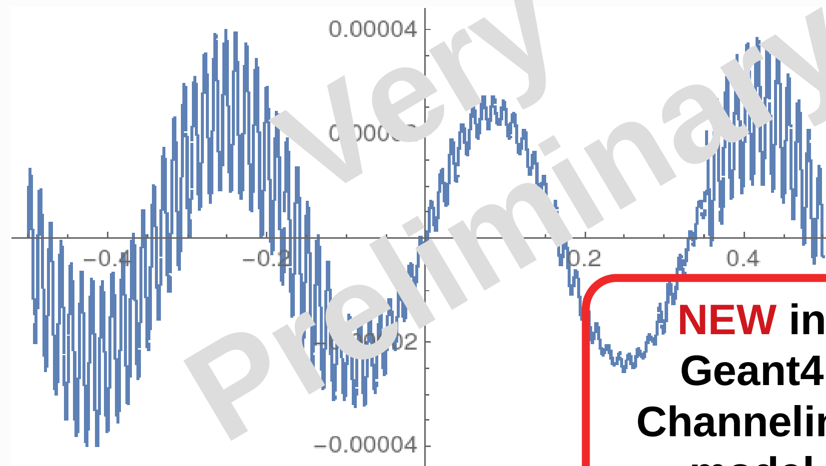
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



Advantage:

- Intense X- and gamma-rays produced in a crystal, in a compact piece of material

Innovative scheme: Crystalline undulator-> Hard X-rays and gamma rays λ_u < mm



NEW in Geant4 Channeling model

Crystalline X and gamma-ray source **can be applied** in:

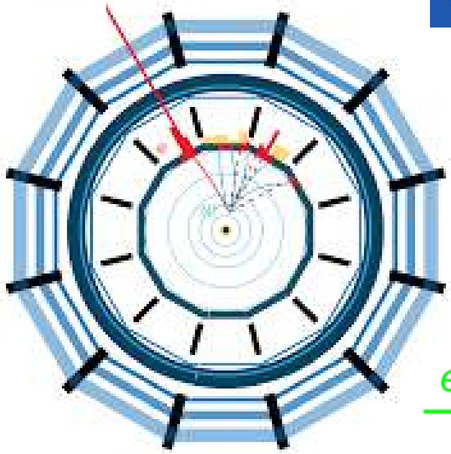
- **Nuclear physics**
- **Medical physics**

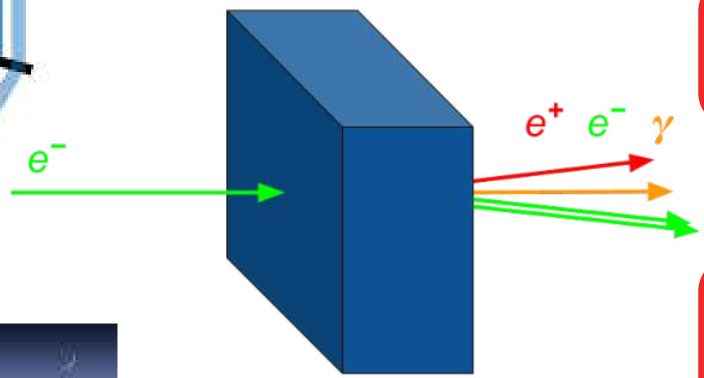
H2020-MSCA-RISE N-LIGHT (G.A. 872196) and
EIC-PATHFINDER-OPEN TECHNO-CLS (G.A. 101046458)
Coordinator MBN RESEARCH CENTER (Germany)

Positron source for future lepton colliders

FUTURE CIRCULAR COLLIDER

CERN





amorphous tungsten

All the future **e+e- colliders** will need an **intense positron source**

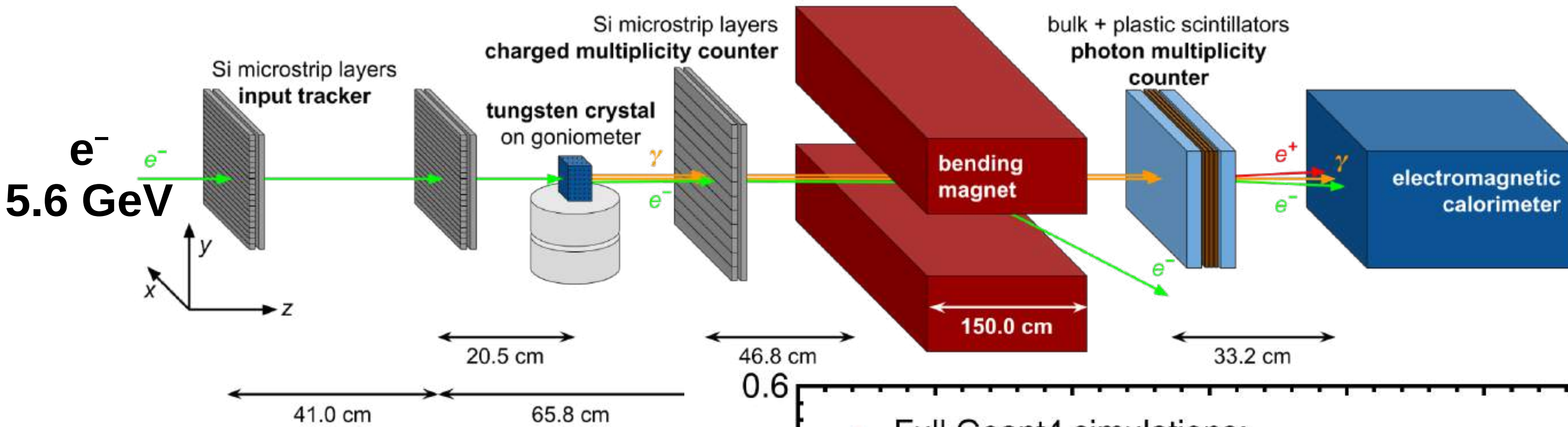
Potential challenges:
Target overheating/melting

Peak Energy Deposition Density (**PEDD**) limit: **35 J/g** for **W***

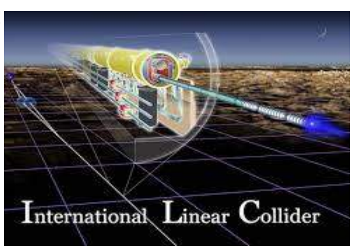
The main **challenge**:
to **increase positron yield** and to **decrease PEDD**

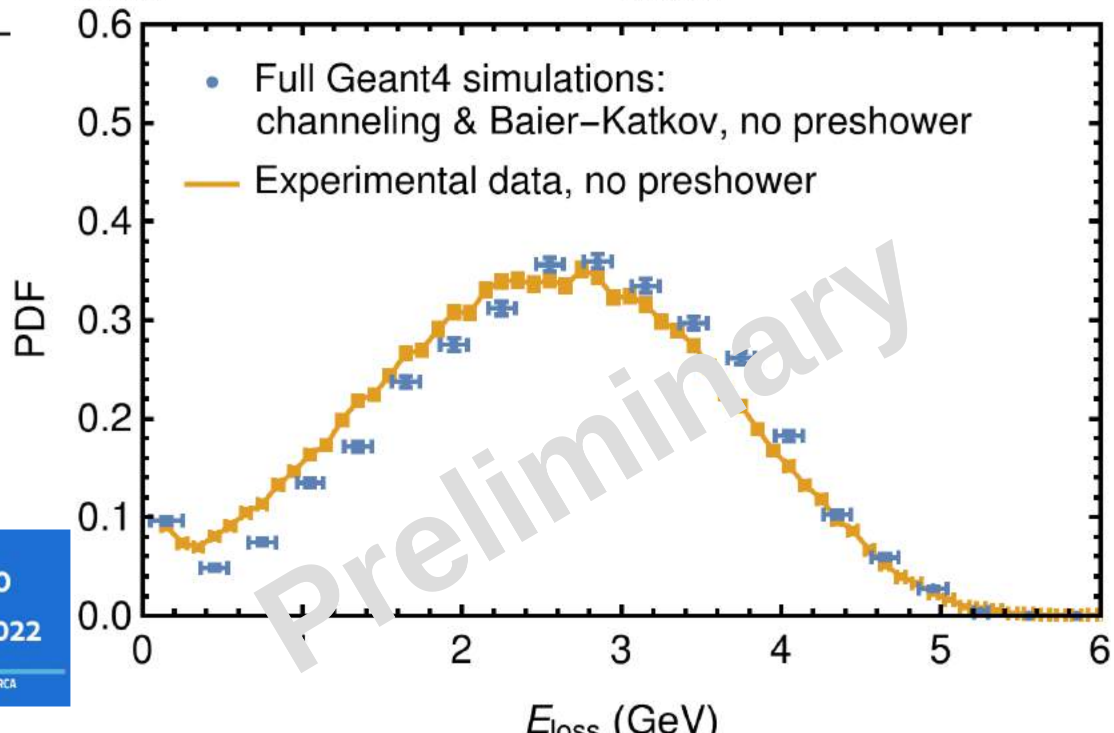
*S. Maloy et al., Slc target analysis. LANL LA UR-01-1913 72 (2001)

Full Geant4 simulations of the DESY experiment*
for the FCC-ee positron source project



FUTURE CIRCULAR COLLIDER





Intense positron source Based On Oriented crySTals - e+BOOST
(PI L. Bandiera)
PRIN2022-2022Y87K7X

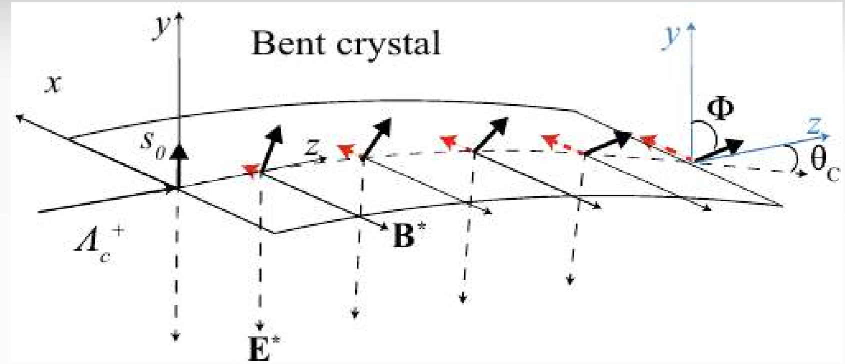
Financed by Italian Ministry of University and Research - PRIN project

Additional applications of oriented crystals

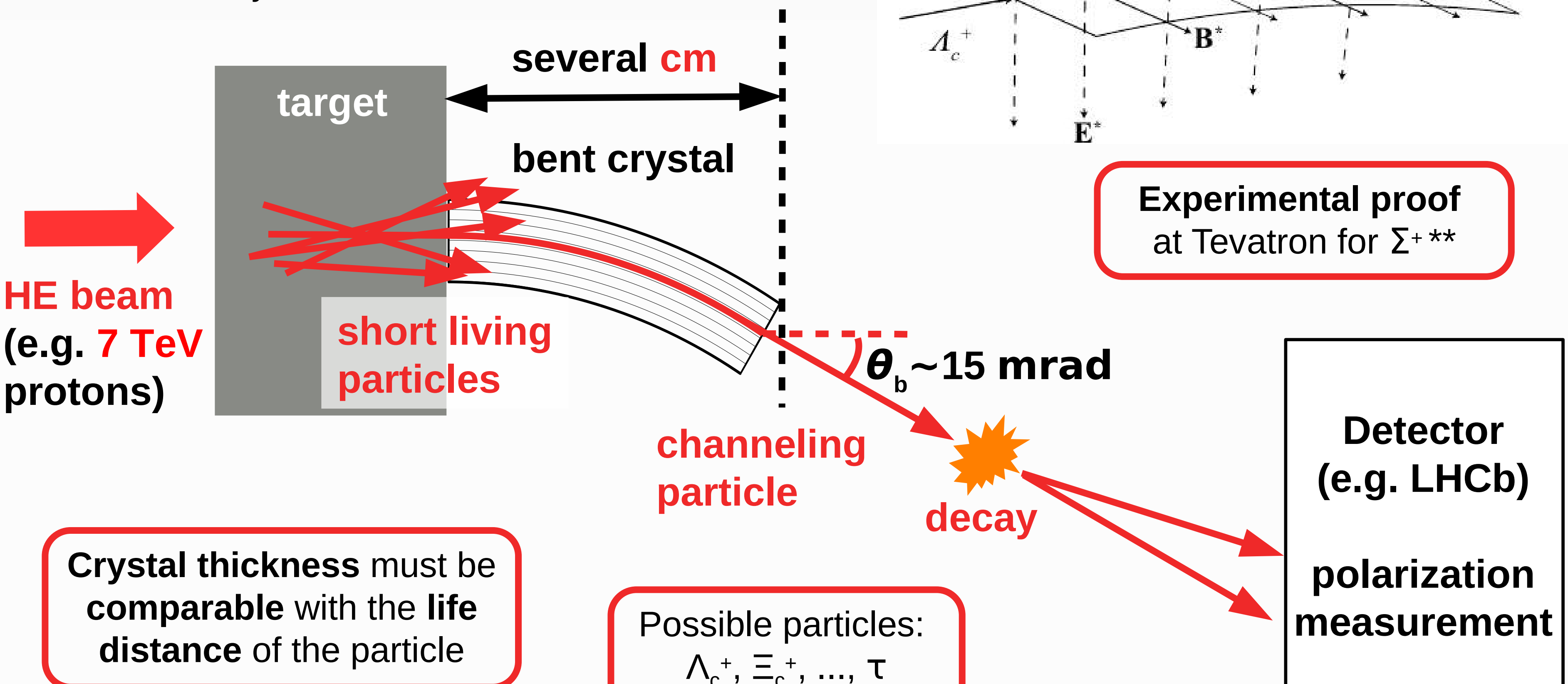
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

What we want:

- To measure **MDM** and **EDM** of exotic baryons



Experimental proof at Tevatron for Σ^+ **



Crystal thickness must be **comparable** with the **life distance** of the particle

Possible particles: Λ_c^+, Ξ_c^+, ..., τ

* V. G. Baryshevskii, Pis'ma Zh. Tekh. Fiz. 5, 182 (1979)

**D. Chen et al. (E761 Collaboration) Phys. Rev. Lett. 69, 23 (1992)

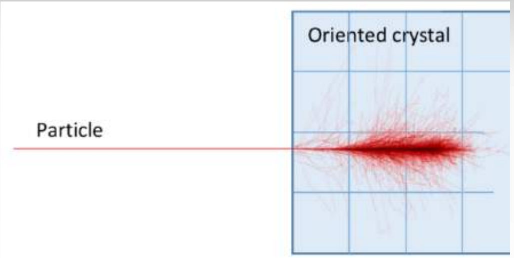
Crystal-based ultrashort electromagnetic calorimeter* (The INFN OREO experiment ORiEnted calOrimeter)

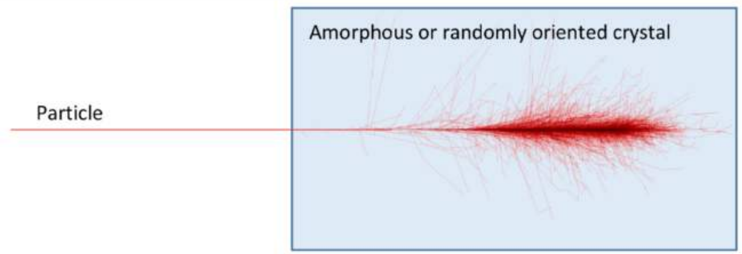
Advantage:

- Considerably shorter thickness
- More transparent for other particles (hadrons)
- Potentially lower time resolution

Crystalline calorimeter can be applied at:

- Fixed-target experiments including **dark matter search**
- **Space gamma telescopes => GRB** observation





CERN North Area

HIKE

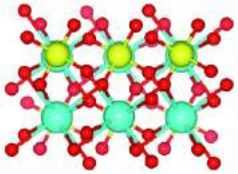
High Intensity Kaon Experiments

$$K_L \rightarrow \pi^0 \nu\nu$$

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

PWO



Cristalline calorimeter extends observation **γ energy range** up to **TeV**

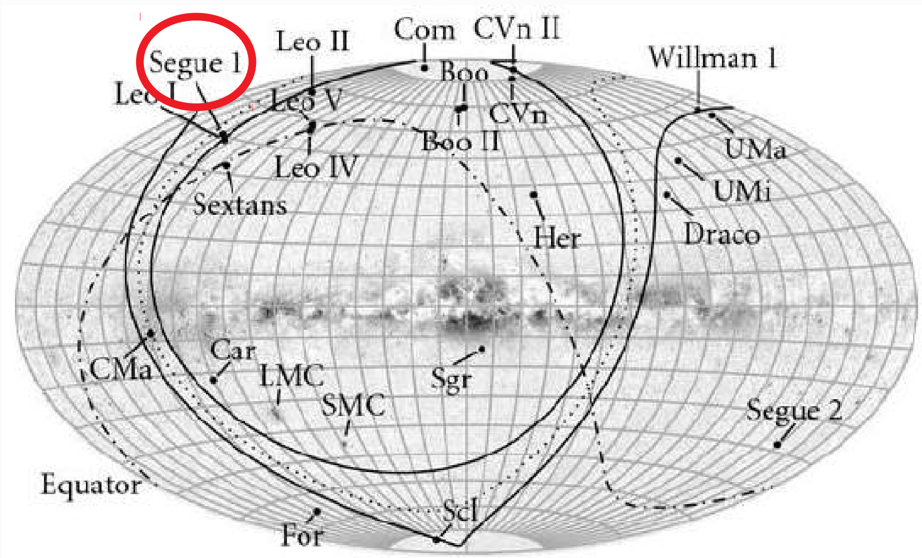
Dwarf spheroidal galaxies (dSph) as dark matter laboratories

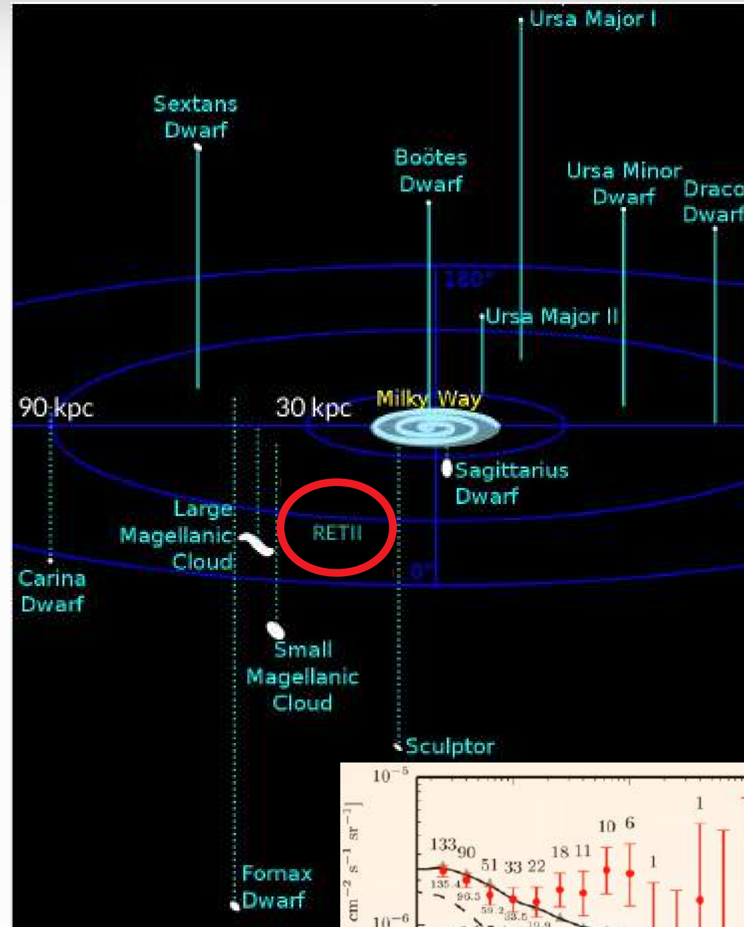
BROWN UNIVERSITY

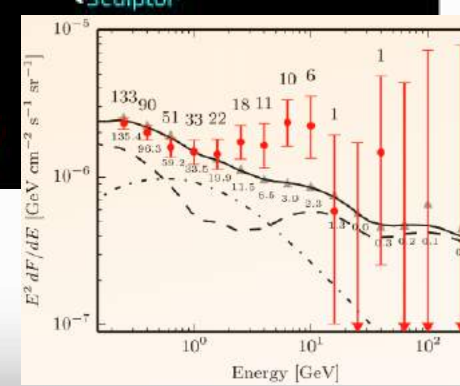
Why dwarf galaxies for the dark matter search?

Dwarf galaxies are:

- **nearby**,
- **dark matter-dominated**,
- contain **no conventional sources** of astrophysical **backgrounds** (e.g., cosmic ray generation and propagation through interstellar gas)



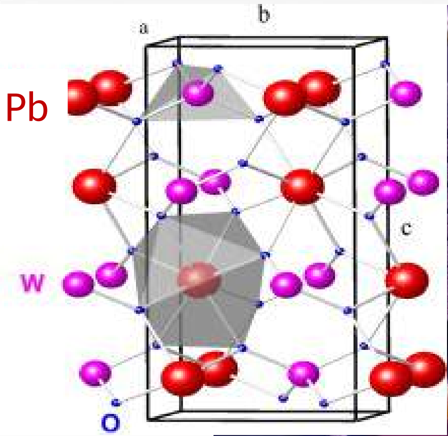




More than **50 dwarf galaxies** are currently **known**, with more to be discovered with upcoming surveys!

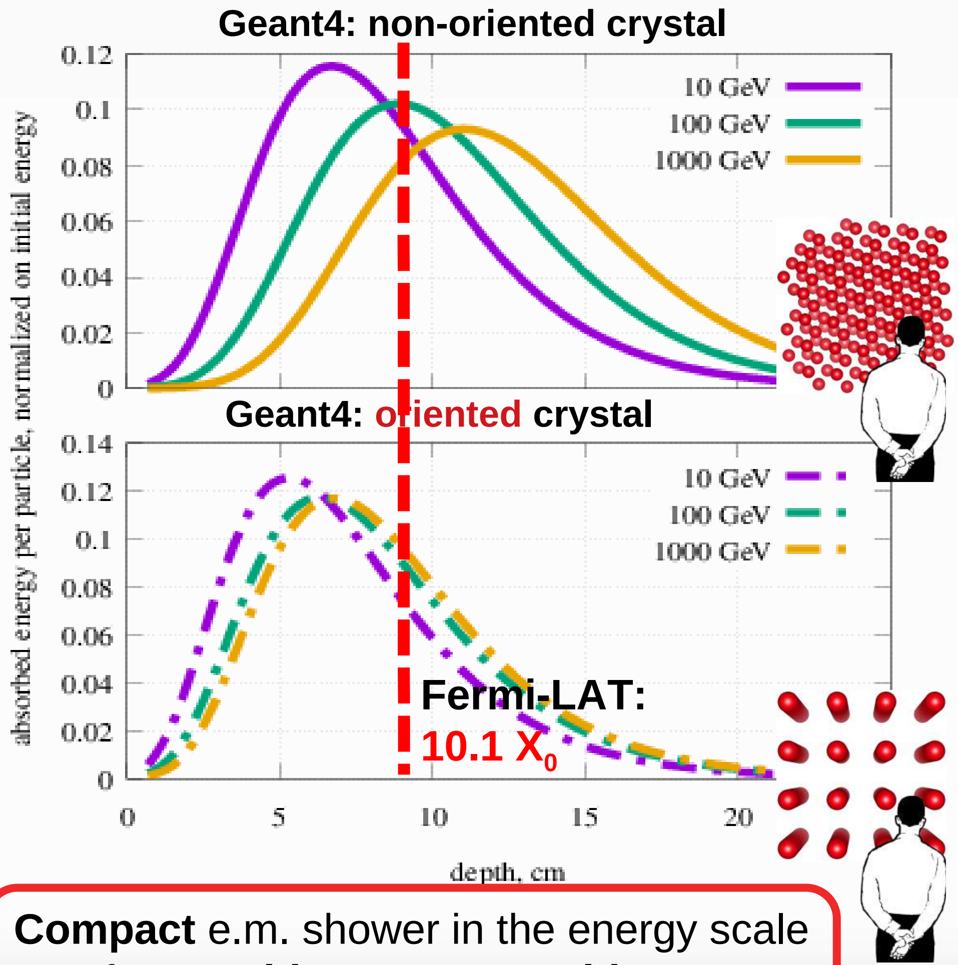
Orienting the electromagnetic calorimeter => making it thinner!

Lead tungstate: $PbWO_4$



INFN OREO by L. Bandiera et al.

Simulation of the e.m. shower of HE electrons in a PWO crystal

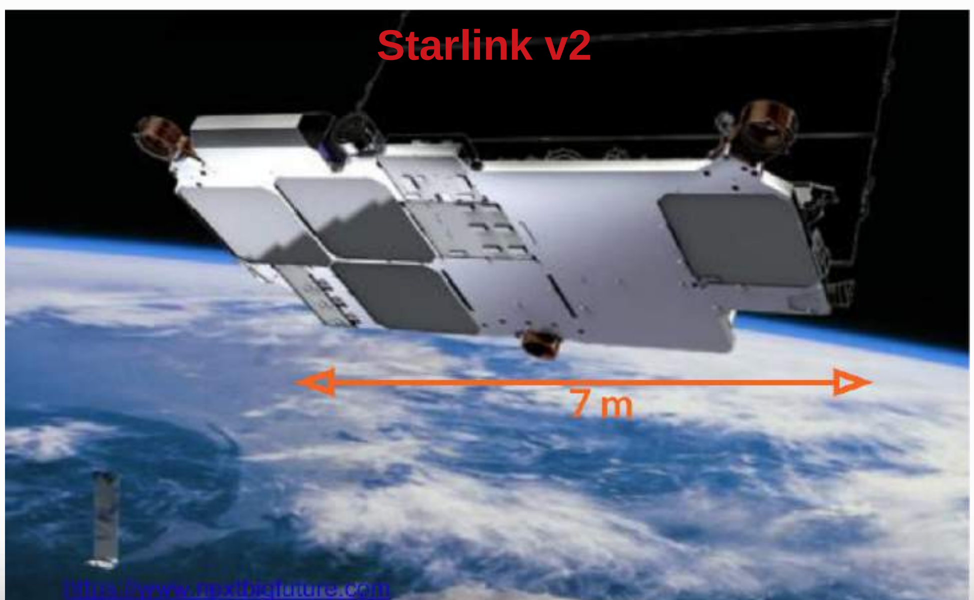


Compact e.m. shower in the energy scale from **multi-GeV** up to **multi-TeV**!

Starlink Satellites v1.5, v2 mini, and v2

Starlink

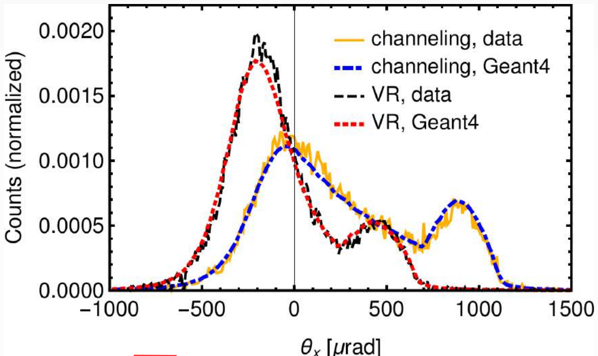
- **Starlink v1.5** (270 kg, launched in SpaceX Falcon 9, 51 per launch)
- **Starlink v2 Mini** (800 kg, 21 launched at a time in SpaceX Falcon 9), **Body 11 m2**, Panels 105 m2 (May 2023) 4,400 sat. already launched >90% fully operational
- **Starlink v2** (~50 per launch in future SpaceX Starship) Body 25 m2, 1200 kg



What about Neural Nets? My proposal

Geant4 simulations can produce **datasets** for **neural nets training.**
Neural nets are less precise but **much faster**!

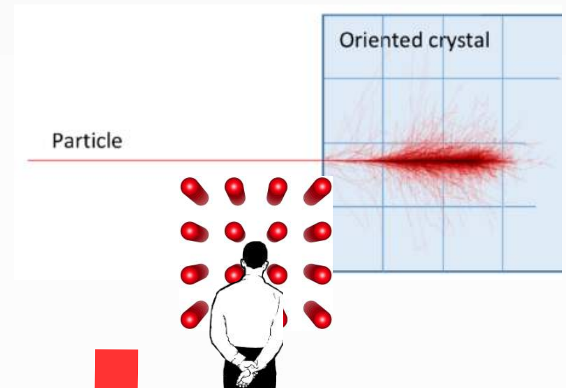
Step 1: beam deflection




```
Layer (type)                 Output Shape              Param #
=================================================================
dense (Dense)                (None, 200)               800

dense_1 (Dense)              (None, 500)               100500

dense_2 (Dense)              (None, 1000)              501000

dense_3 (Dense)              (None, 500)               500500

dense_4 (Dense)              (None, 200)               100200

dense_5 (Dense)              (None, 100)               20100
=================================================================
Total params: 1,223,100
Trainable params: 1,223,100
Non-trainable params: 0
```

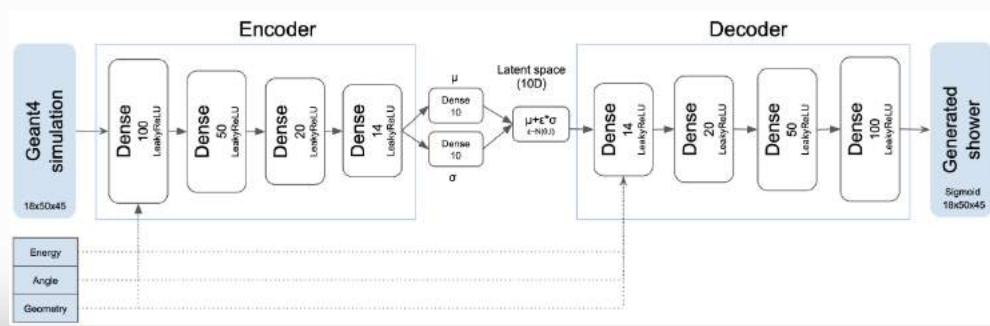
My first attempt

Step 2: electro magnetic shower



Korea Institute of Science and Technology Information
www.kisti.re.kr

To use the **variational autoencoder** model already existing in **Geant4**
Anna Zaborowska & Marc Verderi



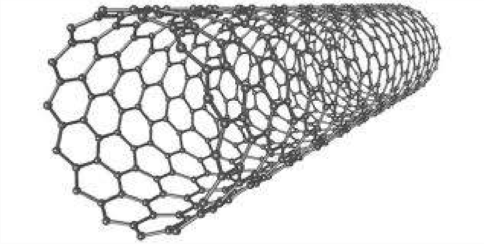
Plasma wake-field acceleration in nanostructures

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Acceleration gradient: $1\text{-}10\ \mathrm{TeV/m}$

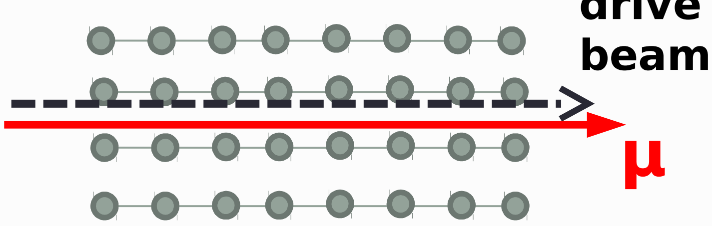
Considerably **higher electron density** in a **solid state** than in a gaseous plasma

Channeling makes **crystal** almost **transparent** both to accelerated and to drive beam



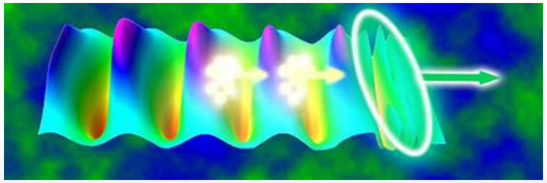
Possible drive beam:

- **X-rays**
- **electrons**
- **heavy high-Z beams**



Possible accelerated beam:

- **muons**
- **e+/e-**
- **protons**

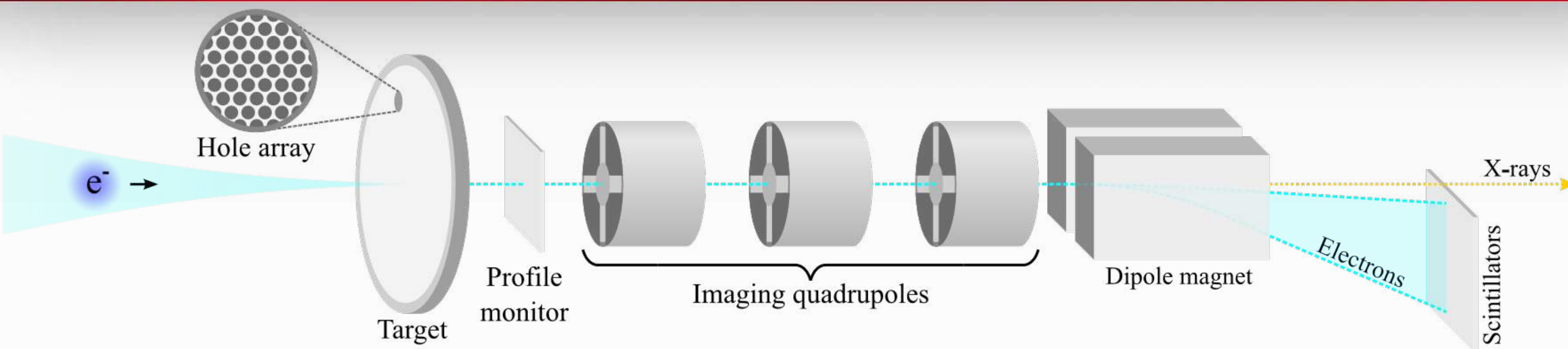


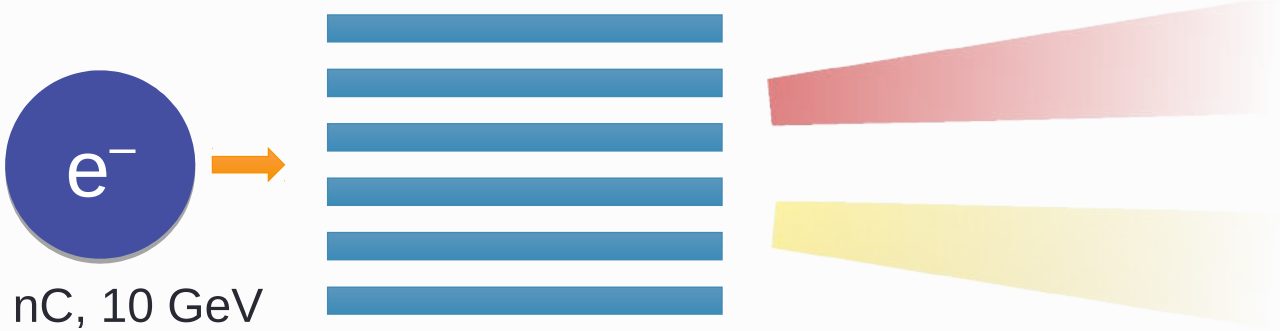
Compact muon collider?

* Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

E336 SLAC FACET-II experimental setup





2 nC, 10 GeV
1-10 µm

Structured
target

To measure:

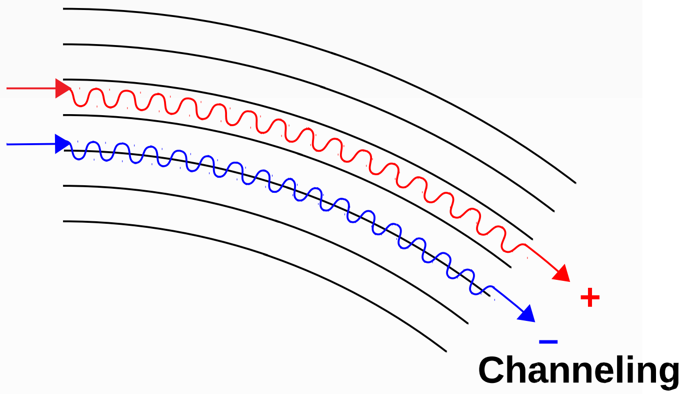
Transverse momentum distribution & other beam parameters

X-rays
Gamma-rays

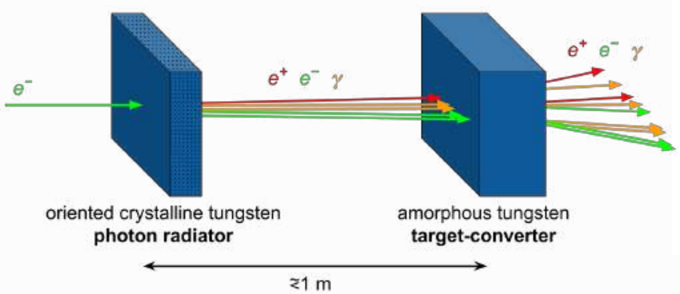
Observation of transverse plasma waves

Let's dream about future lepton colliders!

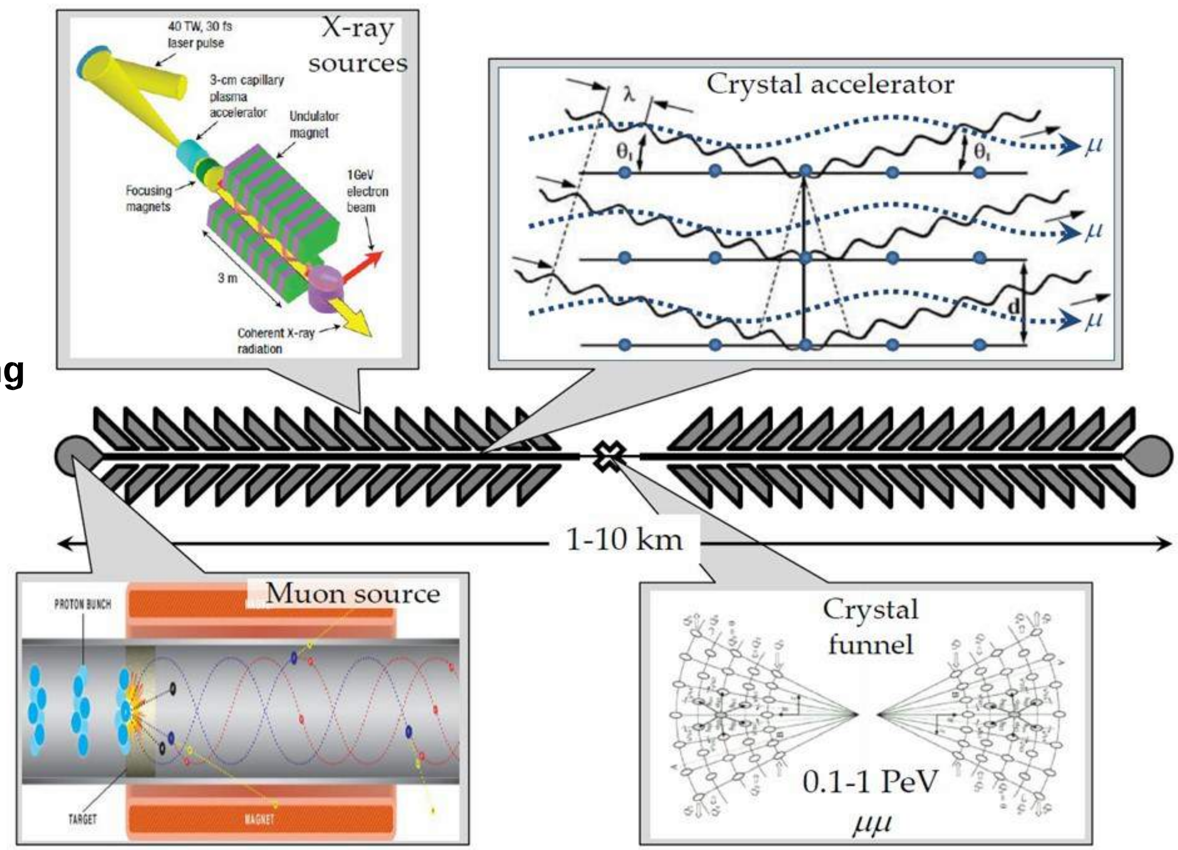
Channeling in a bent crystal



Hybrid crystal-based positron source**



Concept of a linear X-ray crystal muon collider*,**



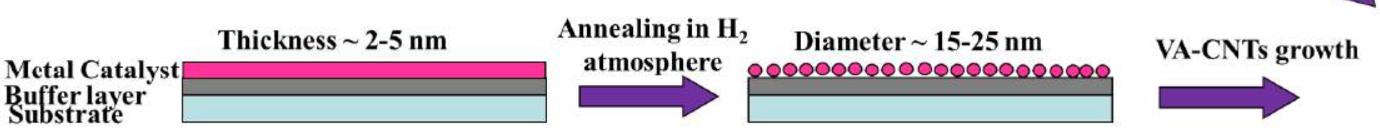
***L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

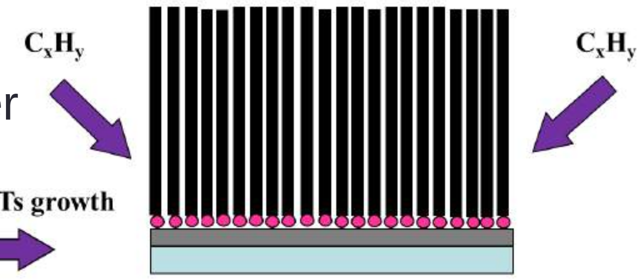
**V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)

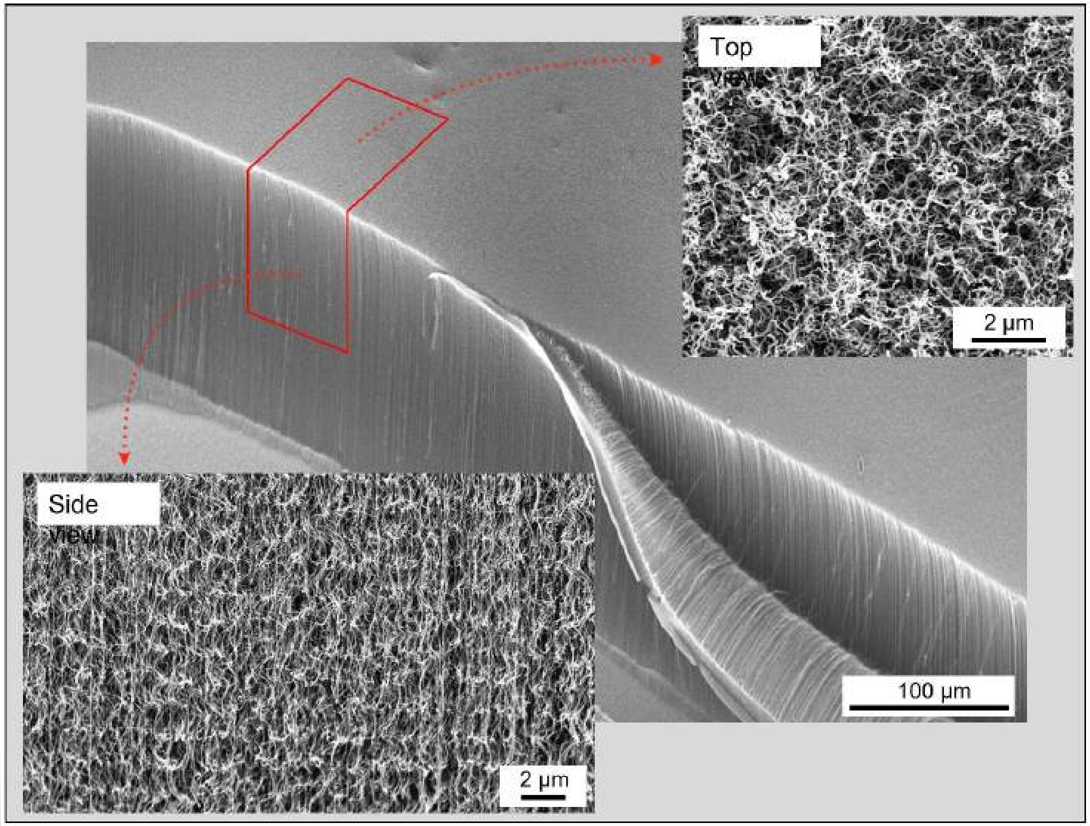
** Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

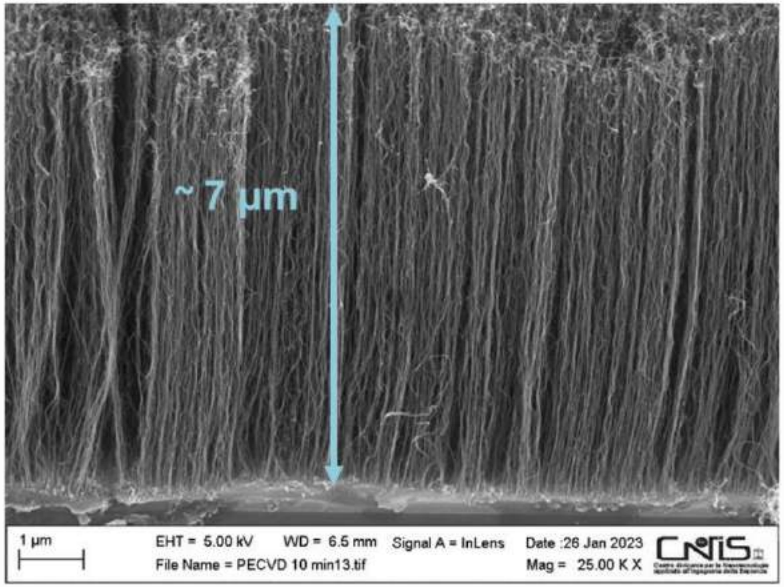
Future target: carbon nanotubes

Thermal decomposition of a gaseous precursor on catalytic nanoparticles in a high-vacuum reaction chamber









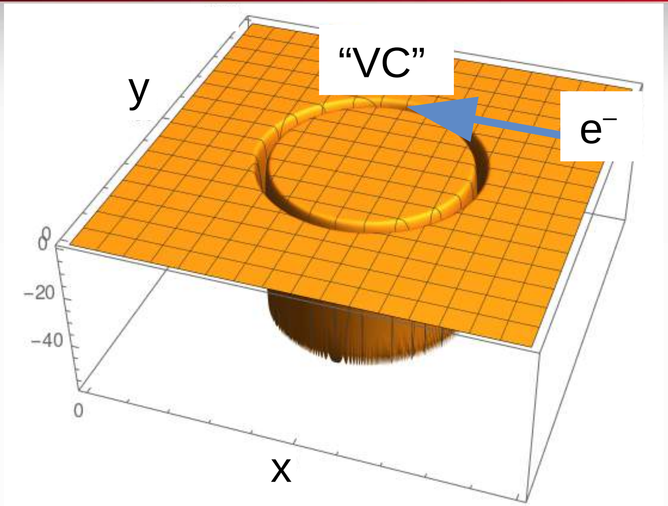
Courtesy of
Prof. Gianluca Cavoto,
Dr. Ilaria Rago

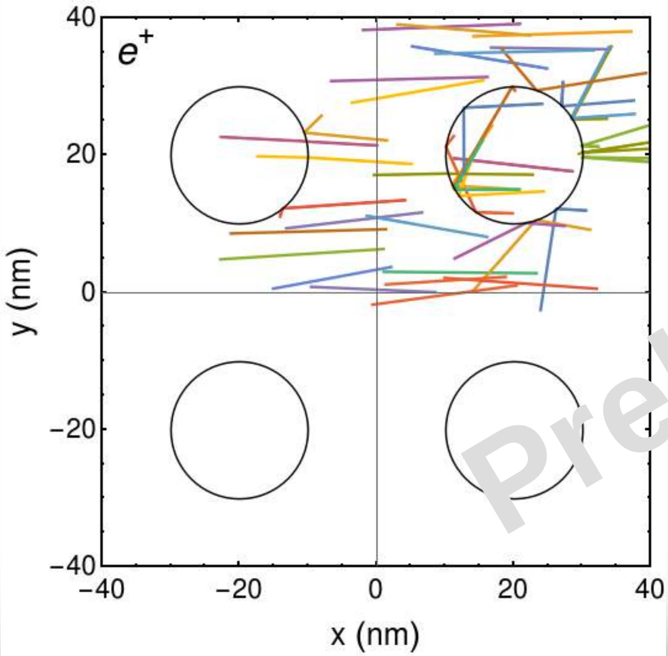
* F. Sarasini et al. Composites Part B 243 (2022) 110136

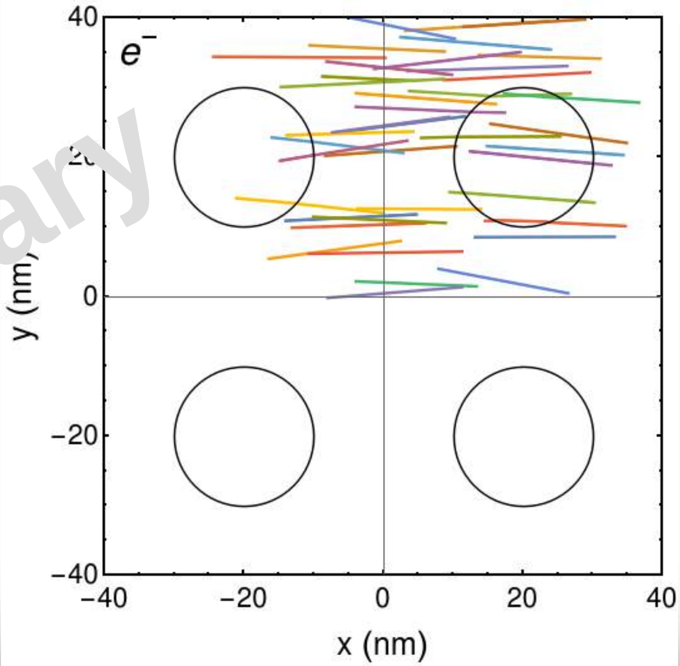
Channeling simulations in CNT: trajectories, ideal case

Simulations with **CRYSTALRAD** simulation code*

Simulation parameters:
Beam: e^-/e^+
Divergence: 10 µrad
CNT diameter: 20 nm
CNT length: 0.2 mm





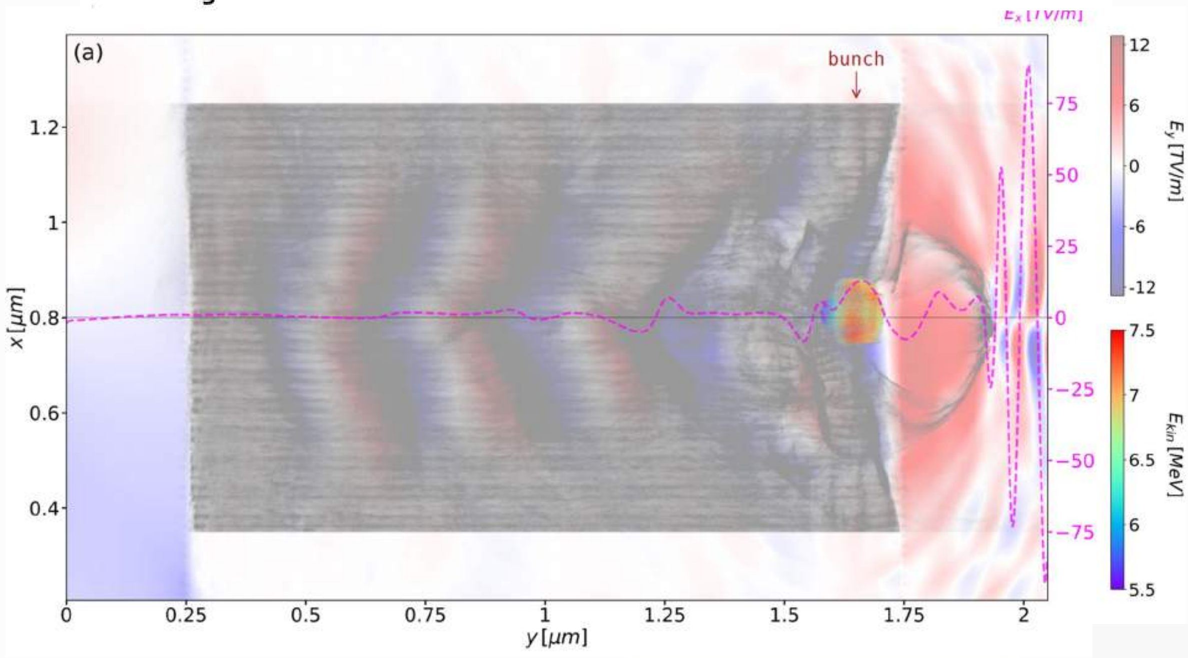


*A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Laser plasma acceleration in carbon nanotubes

TeV/m catapult acceleration of electrons in graphene layers

Cristian Bonțoiu[1,2], Öznur Apsimon[2,5], Egidijus Kukstas[1,2], Volodymyr Rodin[1,2], Monika Yadav[1,2], Carsten Welsch[1,2], Javier Resta-López[3], Alexandre Bonatto[4] & Guoxing Xia[2,5]



VNIVERSITAT DE VALÈNCIA

UNIVERSITY OF LIVERPOOL

MANCHESTER 1824 The University of Manchester

UFRGS UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

*C. Bonţoiu et al. Nature Scientific Reports 13:1330 (2023)

Collaboration with Pohang Acceleration Laboratory

PAL
POHANG ACCELERATOR LABORATORY

10 GeV electrons in beam dump

Our collaboration topics

- **laser/X-ray plasma acceleration**
- **positron source**
- **beam deflection/X-FEL diagnostics**

TRILLION synergy with different fields

- Beam manipulation: **e-/e+/proton/... synchrotrons/colliders**
- Positron source: **FCC-ee**
- Radiation source: **crystalline undulator**
- Detector physics: **electromagnetic calorimeter**
- **MDM** and **EDM measurement**
- **Space gamma-telescopes for dark matter search**
- **Machine Learning**
- **Beam-driven plasma acceleration in nanostructures**
- **Laser-driven plasma acceleration in nanostructures**

TRILLION initially:

Host:

INFN
Istituto Nazionale di Fisica Nucleare

Geant4 collaboration:

GEANT4
A SIMULATION TOOLKIT

Planned secondments:

DESY.

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Partner for outgoing phase:

KiSTi
www.kisti.re.kr
Korea Institute of Science and Technology Information

My Project MIRACLE (supercomputing time):

CINECA

Laser-driven plasma wakefield acceleration in nanostructures:

PAL
POHANG ACCELERATOR LABORATORY

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UNIVERSITY OF LIVERPOOL

MANCHESTER 1824
The University of Manchester

UFCSPA
Universidade Federal de Ciências da Saúde de Porto Alegre

TRILLION synergy with: H2020-MSCA-RISE N-LIGHT, EIC-PATHFINDER-OPEN TECHNO-CLS:

MBN Research Center

Gamma-ray space telescope for dark matter search:

BROWN UNIVERSITY

E-336 experiment at SLAC FACET-II:

Fermilab

l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

loa

cea

Experiments for code validation:

CERN

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

NA62:

CERN

Geant4& medical physics:

UNIVERSITY OF WOLLONGONG AUSTRALIA

MU2E:

Fermilab

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford

FACET-II Facility for Advanced Accelerator Experimental Tests

ist TÉCNICO LISBOA

UCI

IPAC22

ICHEP 2022 BOLOGNA

ICABU 2022

IPAC23

KPS 70th Anniversary and 2022 Fall Meeting
Oct. 18(Tue) – 21(Fri), 2022
BEXCO Convention Hall, Busan

2022 KOREA SUPERCOMPUTING CONFERENCE
HPC makes the future!

NanoAc 2022

2023 KPS Spring Meeting
April 19(Wed) ~ 21(Fri), 2023
Daejeon Convention Center (DCC) & IBS Science Culture Center (IBS SCC)

GEANT4 27th Geant4 Collaboration Meeting

International Symposium on Grids & Clouds (ISGC) 2023

High1 Workshop on Particle, String and Cosmology
Jan. 29 - Feb. 4, 2023 High1 Resort

The 1st Yemilab Workshop

GEANT4
IV Geant4 International User Conference at the physics-medicine-biology frontier

9th International Geant4 Tutorial in Korea 2022

59th Geant4 Technical Forum

ASAP 2023

Channeling 2023

XV International Conference on Gravitation, Astrophysics and Cosmology (ICGAC15)

28th Geant4 Collaboration Meeting

Geant4 Training Course in Medicine 2023

2023 Korea Supercomputing Conference

2023 KPS Fall Meeting

ICABU 2023

RREPS23

10th International Geant4 Tutorial in Korea 2023
Date: 2023.11.6~10
Place: Jeju National University, Jeju, Korea
Since 2012

A. Sytov TRILLION short **internships** to the INFN group of the **Geant4** collaboration (Laboratori Nazionali del Sud, Catania, Italy):

- 13/09/2021-17/09/2021
- 27/10/2022-28/10/2022
- 14/05/2022-19/05/2022

INFN LNS

A. Sytov TRILLION research expeditions to CERN:

- 03/08/2022 – 18/08/2022
- 07/06/2023 – 13/06/2023

CERN

Publications

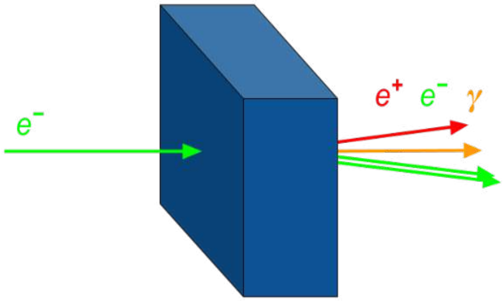
TRILLION publications:

- A. Sytov et al. Journal of the Korean Physical Society 83, 132-139, (2023). DOI: https://doi.org/10.1007/s40042-023-00834-6 arXiv:2303.04385
- L. Bandiera, ..., A. Sytov, et al. Eur. Phys. J. C 82, 699 (2022). DOI: https://doi.org/10.1140/epjc/s10052-022-10666-6
- A. Sytov et al. Eur. Phys. J. C 82, 197 (2022). DOI: https://doi.org/10.1140/epjc/s10052-022-10115-4
- M. Romagnoni, ..., A. Sytov et al. Crystals 12 (9), 1263 (2022). DOI: https://doi.org/10.3390/cryst12091263
- M. Romagnoni, ..., A. Sytov et al. Eur. Phys. J. D 76, 135 (2022). DOI: https://doi.org/10.1140/epjd/s10053-022-00439-x
- M. Soldani, …, A. Sytov et al. Eur. Phys. J. C 83, 101 (2023). DOI: https://doi.org/10.1140/epjc/s10052-023-11247-x
- L. Bandiera, …, A. Sytov et al. Frontiers in Physics 11 Pages: 1254020 (1-11) (2023). DOI: https://doi.org/10.3389/fphy.2023.1254020
- Max F. Gilljohann, …, A. Sytov et al. JINST 18, P11008 (2023) DOI: 10.1088/1748-0221/18/11/P11008 arXiv:2203.07459
- K. Park, K. Kim, A. Sytov, K. Cho. J. Astron. Space Sci. 40 (4), 259-266 (2023). DOI: https://doi.org/10.5140/JASS.2023.40.4.259
- M. Soldani, …, A. Sytov et al. Nuclear Instruments and Methods in Physics Research, Section A 1058, 168828 (1-6) (2024) DOI: https://doi.org/10.1016/j.nima.2023.168828
- L. Bandiera, …, A. Sytov et al. Nuclear Instruments and Methods in Physics Research, Section A 1060, 169022 (2024). DOI: https://doi.org/10.1016/j.nima.2023.169022
- K. Park, K. Kim, A. Sytov, K. Cho. Journal of the Korean Physical Society, 84, 403–426, (2024). DOI: https://doi.org/10.1007/s40042-024-01005-x

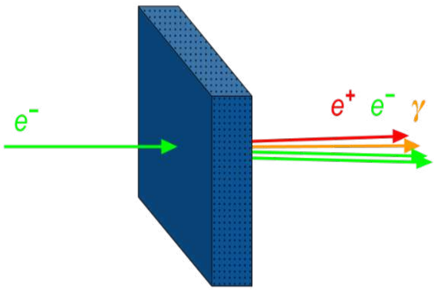

GANGNAM STYLE
Thank you! 감사합니다 !

Different types of crystal-based positron source*

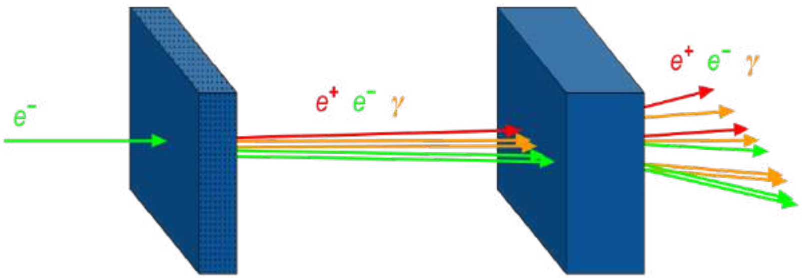
Conventional target



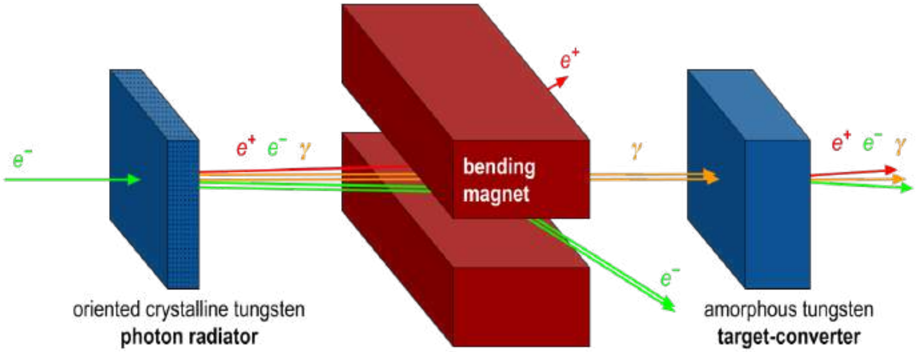
Crystal target



Hybrid scheme



Hybrid scheme with magnetic field

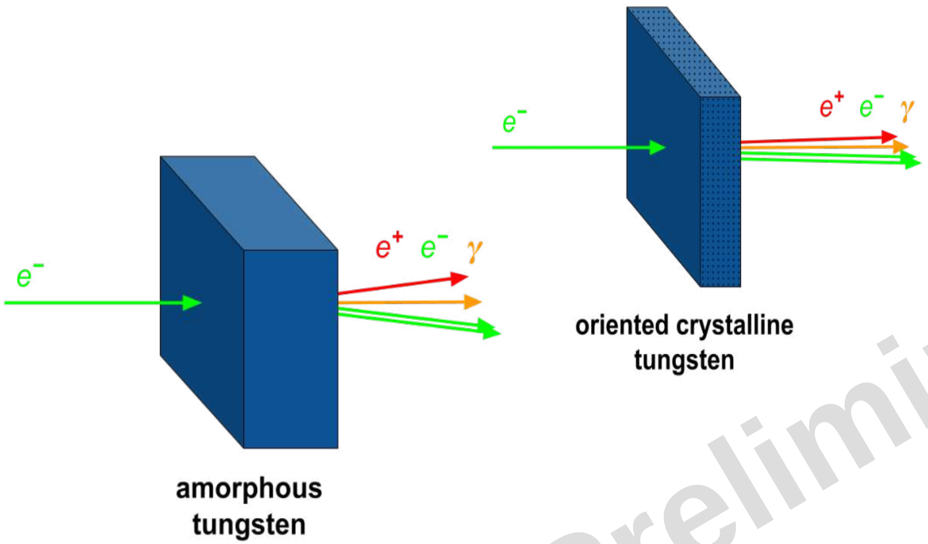


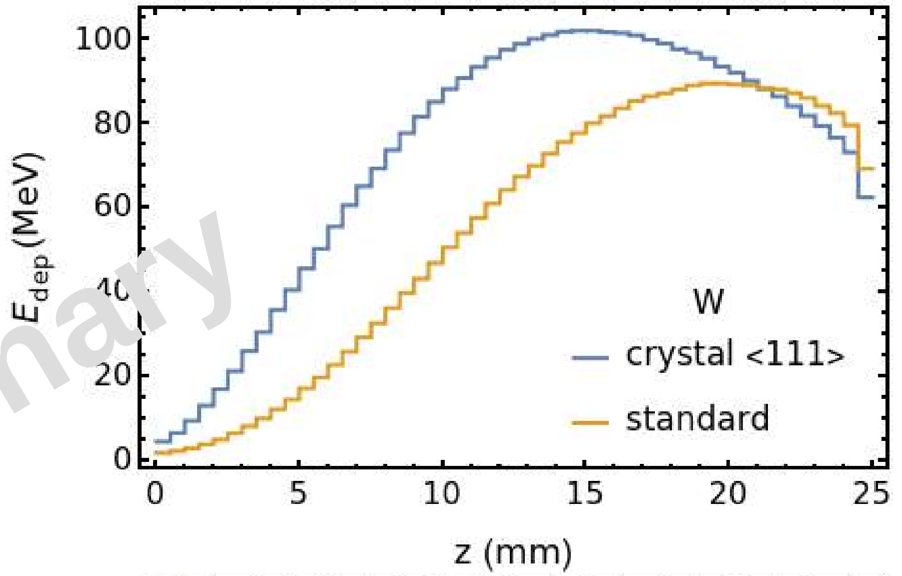
Hybrid positron source: two stages

- **1. Radiation production** and **beam scattering** at the first target
- **2. pair production** in the second target
- Optional magnetic field between 2 targets to reduce PEDD at the second target

positron yield increase
PEDD reduction

FCC-ee positron source project: new simulations





Preliminary